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Invited

Recent Developments in Gallium Nitride Micro-Light-Emitting Diode Structured Light Sources

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ABSTRACT

New formats of fast response display technology are emerging based on micron-sized-pixel inorganic semiconductor light-emitting diodes, in particular utilizing gallium nitride. This so-called micro-LED technology can be bonded or printed onto pitch-matched CMOS control electronics to implement digital-to-light conversion for various modes of operation. Projection of the output of such displays is permitting new developments in visible light based optical communications, positioning, tracking, imaging and sensing systems.

1 INTRODUCTION

Fabricating gallium nitride and AlInGaP/GaAs inorganic light-emitting diodes in the form of micro-scale pixels – so-called micro-LEDs – is facilitating the emergence of new formats of scalable, high-brightness and very fast response electronic visual display technology. The individual micro-LED pixels, of typical diameter/dimension 1-50μm, show nanosecond temporal response leading to modulation bandwidths of several hundred MHz to above 1GHz and can give spectrally-selective output at wavelengths from the deep ultraviolet to red depending upon the epi-structure and material. With high-level data encoding techniques such as orthogonal frequency division multiplexing (OFDM), single micro-LED pixels have been shown to provide optical wireless communications links with data rates of several Gb/s over multi-meter distances, for use e.g. inside buildings, outdoors and even underwater. The emission wavelengths of the devices match the spectral response of high-sensitivity Si-based photodetectors, including single-photon avalanche photodiodes (SPADs). With appropriately sensitive detection, such as is provided by SPADs, micro-LEDs can in principle even provide optical communications links over 10's km distances in space, to provide low size, weight and power (SWaP) inter-satellite communications.

High-pixel-density array formats of the devices can be bump bonded or printed onto pitch-matched CMOS control electronics, facilitating digital-to-light converters capable of projecting sophisticated spatio-temporal patterns. In conjunction with solid-state photodetectors or cameras, such systems can combine advanced optical wireless communications capability with tracking, imaging, self-location and other functions. This technology offers prospects for technological convergences between displays, lighting, sensing, imaging and optical communications systems.

This invited presentation will follow a recently published review by the authors [1] in summarizing the pertinent performance characteristics and selected applications scenarios of this new and very promising technology.

2 EXPERIMENT

As noted above, micro-LED technology fits naturally into high-pixel density 1-D and 2-D emitter array formats to provide electronic visual display capability. Digital interfacing of such display is commonly achieved through flip-chip integration with a digitally addressed active-matrix driver chip as illustrated schematically in Figure 1, but alternative approaches such as monolithic integration or transfer-printing have been demonstrated.

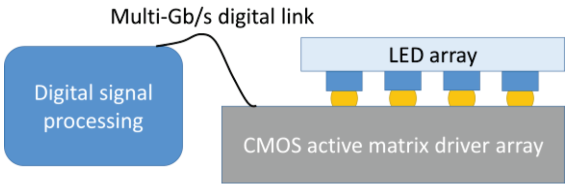

Fig.1 Layout of active matrix micro-LEDs

Furthermore, as also noted in the Introduction, the detailed physics of micro-sized pixels offers enhanced modulation bandwidths into the GHz range per pixel, more than two orders of magnitude higher than that typical of conventional broad area LEDs. These factors can be combined in new forms of spatially multiplexed or spatially modulated Light-Fidelity (LiFi) communications, such as space-shift keying (SSK) or multiple input multiple output (MIMO), to enhance data communications channel capacity. In this format, the display function embodies the spatial registration and/or distribution of information in a communications link, rather than necessarily embodying direct-view images of a scene (the traditional understanding of the function of an electronic visual display). However, the frame rate or image refresh rate is so fast for micro-LEDs that the displays can operate multi-modally, to implement display and spatially modulated communications functions in parallel.

For example, high refresh rate binary mask patterns can be generated with complementary metal-oxide semiconductor (CMOS) interfaced micro-LED displays, at frame rates which may exceed 1 MHz, and at a brightness suitable for projection as illustrated in Figure 2.

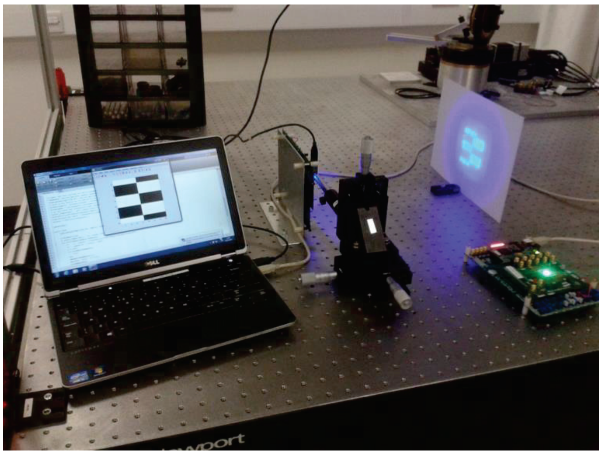

Fig.2 Projection of structured light patterns onto a screen by a 16 x 16 active-matrix driven array of GaN micro-LEDs

Ongoing development efforts with such systems focus on improving array density, frame rates, and optimized digital interfacing with digital signal processing systems. Binary illumination patterns projected at a frame rate beyond visual flicker recognition can carry a data signal, which can be received by high-speed cameras. Such a scheme is illustrated in Figure 3, where the data patterns are updated at half the receiving camera frame rate. Such a micro-LED projector based camera communications scheme is accessible to state-of-the-art mobile phone camera receivers offering frame rates of 960 fps, and the data signal can in principle be overlaid with image or video content running at a much lower frame rate.

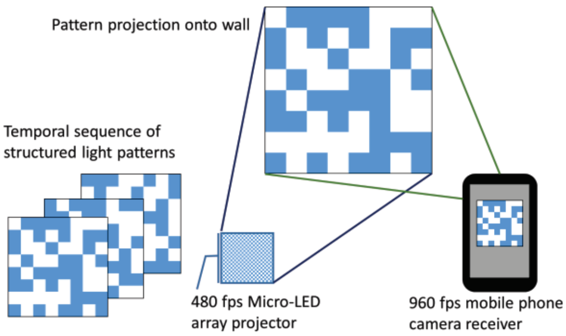

Fig.3 Optical camera communications using structured illumination from a micro-LED projector

The checkerboard-like high-frame rate patterns projected by these systems can also provide unique digital signatures to each location in the projected frame, which can be used to implement location, tracking and navigation functions. Thus the projected output of such a display can be used e.g. to locate and track moving objects in the space around it, potentially including viewers of the display, while also displaying the image or video information required of a conventional display. Compared with other visible light positioning methods, the use of micro-LED display projection requires minimal computational resources, provides straight-forward combination with space-division multiple access LiFi, and is readily scalable through the choice of the projection format.

An additional variant of these digital lighting systems uses LED projections from multiple spatial directions (usually four) in conjunction with a camera to implement photometric stereo imaging. Given the current size scaling of micro-LED displays and the prospective ability to incorporate light sensing functions through front plane or other forms of integration, it is possible in future that the projected output from a micro-LED display (e.g. from its four corners) can also act to image the environment around it. In this configuration, the micro-LEDs are able to provide 3D photometric stereo imaging, visible light positioning through received signal strength, and a LiFi data signal all at the same time.

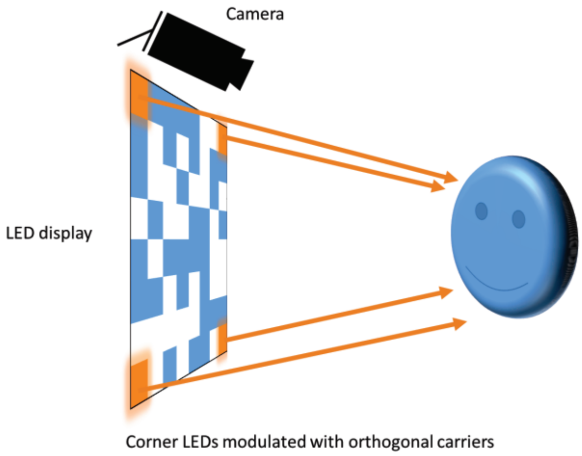

Fig.4 Photometric stereo imaging utilizes illumination from different directions

As illustrated in Figure 4, photometric stereo imaging relies on illumination from different directions, where the camera resolves the differences in surface shading according to each illumination angle. By modulating the corner LEDs with suitable orthogonal multiple access carrier signals, photometric stereo-imaging can be made robust to background illumination from other light sources or the display itself.

The different operating modes of micro-LED arrays are matched to the properties of suited detector technology. LiFi and visible light positioning is often optimized for photo-diodes or avalanche photodiodes, which offer a high bandwidth and a high dynamic range. Optical camera communications and photometric stereo-imaging are usually designed to work optimally with CMOS image sensors. A recent detector technology that offers particularly exciting prospects is silicon single photon avalanche diodes (SPADs) referred to in the Introduction. These devices are fabricated by standard CMOS processes and have a high sensitivity, enabling low light level systems to operate significantly closer to the shot noise limit than with other types of detectors. Furthermore, the individual photon counts by these devices have an exquisite time resolution on the order of 100 ps.

The first active-matrix GaN micro-LED arrays (2008) were specifically designed to operate in conjunction with SPAD detectors, with the target application at the time being fluorescence lifetime imaging. Recent progress in the development of digitally interfaced high density SPAD arrays has reinvigorated the interest in structured illumination systems operating at the few-photon level, extending the application spectrum to 3D ranging, low size, weight and power long distance communications, and temporally encoded multi-spectral imaging.

3 CONCLUSIONS

Micro-LED technology is currently being seen largely as a new form of display technology fitting established device formats and market areas, albeit one which can achieve entirely new levels of performance. This view underestimates the likely impact being offered by the compatibility of this technology with sophisticated control electronics, especially Si CMOS. CMOS-enabled active-matrix control readily accesses the high modulation bandwidths of GaN micro-LED pixels, which are well beyond the switching speeds of other display technologies. Multi-modal operation of displays is now in prospect, where the display can act as both a communications and image representation medium and is also able to sense and interact with its environment in a variety of ways. We will review these exciting emerging capabilities and technological convergences and speculate on how they will develop.

ACKNOWLEDGEMENTS

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