High density, high radiance µLED matrix for optogenetic retinal prostheses and planar neural stimulation

Ahmed Soltan, Brian McGovern, Emmanuel Drakakis, Mark Neil, Pleun Maaskant, Mahbub Akhter, Jun Su Lee, Patrick Degenaar Member, IEEE

Abstract—Optical neuron stimulation arrays are important for both in-vitro biology and retinal prosthetic biomedical applications. Hence, in this work, we present an 8100 pixel high radiance photonic stimulator. The chip module vertically combines custom made gallium nitride µLEDs with a CMOS application specific integrated circuit. This is designed with active pixels to ensure random access and to allow continuous illumination of all required pixels. The µLEDs have been assembled on the chip using a solder ball flip-chip bonding technique which has allowed for reliable and repeatable manufacture. We have evaluated the performance of the matrix by measuring the different factors including the static, dynamic power consumption, the illumination, and the current consumption by each LED. We show that the power consumption is within a range suitable for portable use. Finally, the thermal behavior of the matrix is monitored and the matrix proved to be thermally stable.

Index Terms—Optogenetics, ChR-2, µLEDs, Stimulation, Low power, Retina, GaN LEDs

This paragraph of the first footnote will contain the date on which you submitted your paper for review.

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I. INTRODUCTION

Optogenetics, a gene-therapy technique for photosensitizing cells, is becoming an increasingly mature tool for biomedical research [1 – 4]. It could also form the basis for next generation neuroprosthetic therapies such as visual prosthesis [5, 6] and epilepsy [7, 8]. Photosensitization is achieved through modifying the cell’s genetic code to produce light-sensitive ion channels or pumps. Commonly, cation channels such as channelrhodopsin-2 (ChR-2) [9, 10] or variants thereof have been used for optical depolarization (stimulation). Chloride pumps such as halorhodopsin [5] hyperpolarize cells by pumping in chloride ions and have thus been used for inhibition. Such channels and pumps can be used either in isolation or in tandem. For the latter, addressability can be achieved via wavelength selectivity.

Light-based stimulation has certain advantages compared to the electrical stimulation devices [12 – 16]. These include biocompatibility, genetic targeting of the neural sub-circuits, and the ability to simultaneously stimulate and record (electrically). However, the key caveat is that the threshold for activation of optogenetically encoded cells is very high. Classically this is 0.7mW/mm^2 (=0.7nW/µm^2) [1, 6, 17] in pulses of around 10ms for wild-type ChR2.

Specifically, with regards our interests in retinal prosthetics, Bi et. al. noted the 1mW/mm^2 requirement to achieve full dynamic range when stimulating retinal ganglion cells [5]. In contrast, Lagali et al noted a requirement of 10^4 mW/mm^2 in retinal bipolar cells [2], and Busskamp et. Al. noted a requirement of 10^5 mW/mm^2 in reactivated cone cells [9]. Such differences in response relate to differences in cell physiology,
gene expression and the effect of the neural architecture. Furthermore, some advanced variants of ChR2 (and delivery thereof) require less light. Given the published work, we assume the required irradiance on cells to be between 0.1mW/mm² to 1mW/mm² [18].

The optical structure of the eye is designed to deliver light to the retina, so an obvious early application for optogenetics is in retinal prosthetics. Retinal prosthesis to bring back sight to the blind has been explored since 1992 when Stone and co-workers discovered that some of the processing and communications cells still functioned in those blinded by the Retinitis Pigmentosa disease [19]. Two primary electronic- neuroprosthetic approaches have been developed: sub-retinal [20, 21] and epi-retinal [21, 22] prosthesis. Both utilize electrical stimulation of remaining retinal cells to impart ‘phosphenes’ – flashing dots of light. Both approaches have also received regulatory approval and have recently become commercially available. The difference between the two relates to where in the retina the stimulating chip is placed. However, in both cases visual return is poor – returning hundreds, rather than millions of effective ‘pixels’ [20, 22].

The clinically available forms of retinal prosthesis provide power through a wireless link. Given the transparency of the eye, a variant of this is to provide power optically rather than wirelessly. Implants can then utilize micro-scale solar cells to convert optical power to electrical power. This was attempted initially by a team based in Illinois which tried to passively acquire optical power in combination with visual information [23, 24]. More recently, a team based at Stanford have developed a system which actively provides optical power and visual information multiplexed from an external source [25].

With optogenetics, it is possible to take the optical retinal prosthesis one step further. In this approach, a remaining layer of the retina can be photosensitized and stimulated with light [26, 2, 9]. An implantable stimulator is therefore no longer required. Instead, the ‘prosthetic’ component would be entirely external consisting of a virtual/augmented reality optical system combined with a high-intensity display.

Consequently, such a system would consist of a camera to capture real-time video and then send images to a processor unit as illustrated in Fig. 1. After that, the processor sends the image sequence to the matrix after applying compression techniques and even power distribution techniques to minimize the power consumption [11]. Light scatters strongly in tissue, thus most light delivery systems for optogenetics have centered on penetrating structures with optical generation [18, 7, 27] or light guided delivery [10, 28 – 31]. However, there is still a requirement for 2-dimensional arrays for both microscopic applications [32 – 34]. In such cases, spatial light modulation has demonstrated capability [35 – 37]. Such approaches may be adapted retinal prosthesis (e.g. by Reutsky-Gefen et al [38]), though ultimately it may be more power efficient to generate only the required light rather than attenuate unwanted light. Additionally, light emissive systems can prove more compact, and efficient.

Our past efforts in this area [18] used lambertian emissive µLEDs at a 150µm spacing. We found that we required a peak emittance of 100mW/mm² [6] in order to achieve a full dynamic range of stimulation. This was because the optical efficiencies in our microscope systems were around 1%. To improve upon this, a more collimated µLEDs emission has been required [39], and a greater density of emissive elements. The latter is not only required to increase resolution but also to improve efficiency – which is proportional to current drive density.

To satisfy the optical array requirements, we have developed a high radiance 2-dimensional array of GaN µLEDs assembled on a CMOS control chip. The control chip allows for high-speed control of each of the elements, while the GaN µLEDs have been tuned to 460nm, which broadly matches the ChR-2 activation spectrum. Our array is 90 x 90 with a pitch of 80µm. This has been limited by our current flip-chip bonding technology and could be extended to much higher density arrays.

II. REQUIRED SPECIFICATION

The required irradiance on cells needs to be 0.01-1 mW/mm², depending on which part of the retina is being stimulated [5, 9]. However, we take the classical 0.7 mW/mm² as a conservative target [1].

We have created our module to combine with an eMagin WFO-5 pyramidal virtual reality lens unit, which as an optical throughput of 60%. The human eye then limits the light throughput via the iris aperture. For typical pupil sizes, this amounts to 20% [40], giving a total optical throughput of 12% (compared to 1% for microscope implementations).

Working on the optical throughput alone, the light requirement would be 5.8mW/mm². However, the WFO-5 optics are designed to image a ~30 x 20 mm display onto a ~9 x 7 mm patch onto the retina. i.e. there is a 9 x minification. This will result in an increase of irradiant density of 9x. Thus our required emittance is 0.57 mW/mm².

For most applications, the highest rate of action potential generation with optogenetics is around 50Hz. Thus, for applications where pulsed stimulus is used to achieve this, the illumination system must have similar response times. i.e. we need to be able to update the pulse width modulation (PWM) pattern of the whole array within 40ms. Similarly, for (retinal) display applications, frame rates of at least 25Hz is required to transfer information without perceptible lag. In order to achieve the radiance density requirements above, we utilize 20µm diameter Gallium Nitride micro light emitting diodes (GaN-µLEDs) with collimating back-optics [41]. Their emission profile can be seen in Fig.2.
The measured current-voltage-luminance and measured current-efficiency profiles of these devices are given in Fig. 3. The turn-on voltage is 2.4V. Although the illumination power increases with increasing the applied voltage, the µLED efficiency reaches the peak value of 2.3 % at a supply voltage of 3.3V and then starts to decrease again. This is part of the well-described ‘droop’ phenomenon [29]. Fig. 3(b) overlays our µLED efficiency profile with another recent example from the literature [42]. It can clearly be seen that the efficiency of LEDs in general drops dramatically with increasing current density. As our application requires high radiiances – we need to drive at high current densities, and thus, the efficiency is of the order of a few percent. Additionally, the light from a single LED is divided across a pixel – defined by the inter-LED spacing. Achieving a high pixel density reduces the light requirement per LED and thus improves efficiency.

In addition to the pixel intensity, the pixel count is important. Although some papers have indicated the possibility of near normal return to vision with an optogenetic retinal prosthesis, more modest resolutions are probably realistic in the near term. Psychophysical studies indicate that at around 5000 pixels a reasonable representation of the visual scene can be achieved [28, 43, 44, 45]. Furthermore, we have chosen the eMagin WFO5 as the target optical delivery system which has a maximum space for the display module at 20mm x 30mm. Thus the created display must fit within those dimensions.

Hence, the key requirements to fulfill planar stimulation system both microscopy and retinal prosthetic purposes are summarized in Table I.

### III. CIRCUIT DESIGN

The global schematic diagram of the 90 x 90 high density µLED matrix is illustrated in Fig. 4. For small arrays such as this, raster scanning of passive pixels would be feasible. However, this would reduce the effective intensity by a factor of N – where N is the number of rows. Thus, we take an active matrix approach where each pixel has a memory unit determining the LED as ON or OFF. Emission intensity is then set globally through voltage control, and locally through pulse width modulation. The matrix consists mainly of three parts; the communication interface, the control logic, and the µLED grid. The pixels are arranged in a matrix form to reduce the control
lines from $N^2$ to $2N$. Control is then via individual pixel, row, or simple raster update [18, 46].

### A. Communication interface

A 4-wire interface is used for the communication with the chip to simplify the routing to the chip. The 4-wires are as follows; activate signal, row data line, column data line and the clock signal. Although, the interface with the matrix is fulfilled through a 4-wire interface. The encoding is illustrated in Fig.

5. A start bit, synchronized to the activate line defines the mode of operation. The mode is thus determined differentially between the Row and Col lines and is summarized in Table II.

### B. Control system

In a normal imaging display, there is typically a normal distribution of intensities around the intensity mid-point. Thus the most efficient method of updating the display is to raster the appropriate values in progressive or interlaced fashion. In a retinal display, it would be expected that the distribution is shifted bimodally between stimulus values and the minimum value (i.e. off). i.e. while there is a distribution of intensities – the majority will be off for any given picture frame [11]. This is of advantage in terms of average power consumption, but it also means there are other options for updating the image. The image intensity is controlled by two techniques; the first one is by controlling the LED voltage which affects the whole matrix emittance level. The second is by utilizing a pulse width modulation (PWM) technique to control the total number of photons being emitted from a given pixel in a given time period [47]. For the PWM based method, the image is divided into sub-frames to construct the PWM waveform.

There are thus two control methodologies

1. **Long-shift**: which based on sending a long 90-bit data packet representing 1 or 0 values for individual columns or rows.
2. **Short shift**: The data packet for row or column is represented by a 7-bit pixel address which is decoded on-chip.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED module size</td>
<td>20 x 30mm</td>
</tr>
<tr>
<td>LED ASIC Size</td>
<td>8mm x 8mm</td>
</tr>
<tr>
<td>Number of µLED</td>
<td>&gt;5000</td>
</tr>
<tr>
<td>Control modes</td>
<td>Pixel and column addressing</td>
</tr>
<tr>
<td>Minimum emittance</td>
<td>0.57mW/mm²</td>
</tr>
<tr>
<td>LED supply voltage</td>
<td>3.5 – 5V</td>
</tr>
</tbody>
</table>

Table I Key requirements of the µLED matrix to fulfill the required stimulation function with a good performance.

<table>
<thead>
<tr>
<th>Row</th>
<th>Col</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Shift – Write</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>Shift – Read</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>Pixel – RST</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Pixel - SET</td>
</tr>
</tbody>
</table>

Table II Summary of the command used to communicate with the chip and the different modes of the serial communication with the matrix where the command is a combination between the first bit send in the row and column bursts.
Fig. 4 Block diagram of the µLED CMOS chip. (a) The pixels are arranged in a matrix order. Shift registers read the information into both row and column, which then update pixel values. Updating can be performed in a single row, over multiple rows, or at individual pixels. (b) The pixel circuit consists of three parts; the pixel logic, the memory unit, and the µLED driver. Periodic buffers on the control lines regenerate control signals.

C. Pixel control

Each pixel contains a one-bit memory cell to store the pixel value as depicted in Fig. 4 (b). Also, the pixel contains a simple
A multiplexer determines the operation between short or long shift depending on the start bit. The combination of these two then allows for:

1. Simple raster: Col values are given in a long 90-bit set of values and a short address given for the row. These are then updated as the rows are updated sequentially.

2. Clustered image: In some cases, multiple rows may have the same values in which case the 90-bits are given for both rows and cols with row values = 1 for replicating rows. Although we included this option, in many practical cases, it simply moves complexity and thus extra processing to the control unit.

3. Pixel update: two 7-bit values can be used to update individual pixels rather than an entire row. This saves clock cycles compared to sending an entire 90-bit address for a row. It is advantageous if 11 pixels or fewer need to be updated for a given row.

Given the options above, the communication is designed for hybrid commands so that individual instructions for either pixel (short-shift) or row/col (long-shift) can be given and needs to be determined by the external control unit.

Hence, the control unit first decodes the received packet to determine which communication mode is intended to be used. Then, it enables the proper shift register (7-bit/90-bit shift register) to send the data to the multiplexer as illustrated in Fig.

4. The multiplexer then enables either a whole column or a certain pixel based on the used communication mode and send logic for pixel selection process and a buffer as shown in Fig.4(b). The buffer is used as a repeater to maintain the signal strength over the long data lines. Indeed, the LED consumes a large current to generate enough light power for the neuron stimulation. Consequently, the driving transistor (M3 of Fig. 4(b)) must be designed wide enough to source enough current for the LED. So, the driving transistor is implemented to supply current up to 10mA at 4V as shown in the measured IV curve of the driving transistor shown in Fig. 14(a).

D. Pixel ESD protection

There is a danger that in the bonding between CMOS and GaN chips, an electrostatic discharge (ESD) event could destroy either a single pixel or multiple pixels. Typically, such protection comes in the form of diode connected pMOS and nMOS transistors which discharge surge voltages to rails. Limiting resistors then limit the current. However, the latter, in particular, can be bulky – which would limit the pixel count. Furthermore, as the main concern is during bonding, there would be no active power supplies at that point anyway.

However, the µLED contact pad is connected to the drain of a large pMOS transistor. As such, this forms diode connections to the substrate, giving some limited protection if the chip is grounded during the bonding process.

IV. IMPLEMENTATION

A. CMOS chip fabrication

The CMOS chip was designed using the Cadence design suite on an xFAB 0.35µm CMOS technology. Fabrication was performed using a multi-layer-mask (MLM) process which allowed the return of a full 8” wafer with a 9mm reticle from which to perform post processing. These wafers were then laser cut into smaller 3” inch wafers for post-processing.

The total chip area is 8mm x 8mm with as illustrated in the mask wafer in Fig 6. The layout of the pixel is also given in the subfigure of Fig. 6. The pad opening for the µLEDs is 34.5 x 30.5 µm with a pixel pitch of 80µm The ESD protection and bond pad ring was created in an L-shape around the chip to allow for combining 4 chips together into a single large matrix array. The chip is designed with two isolated supply pins; the first one for powering the electronic circuits and the second pin for powering the LEDs.

The main limitation for the current driving capability of the circuit is due to the ESD pads and the LED supply tracks inside the CMOS circuit. We thus utilized 26 Vdd_LED pads to provide LED power. The limitation on each is 40mA due to the ESD protection circuits. This gives a total of 1.04A =~ 5W electrical power for a 5V input. Within the chip, the power supply lines are routed in a matrix-like shape to distribute the current between tracks and hence increase the current driving ability for the whole chip. Finally, there are 25 vias on each pixel connection allowing a theoretical 25 mA per pixel before electro-migration effects may be seen.

B. Gallium Nitride LED array fabrication

The Gallium Nitride LED arrays were fabricated on a 2” sapphire/GaN wafer. A schematic layout of the LED wafer is illustrated in Fig. 7(a). A photo for the fabricated wafer is illustrated in Fig. 7(b). In each quadrant of the wafer, there are 3 large 90 x 90 pixel arrays, as well as a number of test structures and process monitors. The emission spectrum of the µLEDs centered at 460 nm with a 22 nm FWHM, which matches the sensitivity spectrum of the ChR2. An individual µLED can be seen in (c), (d).

C. Post-processing and bonding.

The CMOS and Gallium Nitride (GaN) µLED chips need to be both electrically and mechanically connected to each other. To achieve this, we used a solder ball bonding technique, bonding a control pad for each pixel circuit to a corresponding LED anode [48].
To achieve good bonding, the CMOS pixel pads were post-processed using standard photolithographic techniques. A chrome-gold-nickel metal stack was deposited on each bond pad (Fig 8(b)).

Subsequently, solder balls were dispensed using a ball dispensing system from PacTech which attaches the balls to the substrate pad using a heating pulse from a Nd:YAG laser, immediately after deposition. For the best performance, the Pactech solder jet machine uses a solder material consisting of Sn (96.5%)-Ag-(3%)-Cu (0.5%) with solder ball diameter = 50 µm. After configuring the machine, the following steps are followed for the soldering process:

1. Solder ball bumping using Pactech solder bumping machine as shown in Fig. 8(c)
2. Removed the defective solder balls and solder bumping again manually.
3. Flip-chip bonding using the bumped test chips as shown in Fig. 8(d).

![Fig. 6 Chip layout with the ESD pads are placed in L-shape to enable integrating four matrices to build a bigger matrix if needed, also, the pixel layout is shown in the subfigure with the pixel dimension.](image)

![Fig. 7 (a) photograph of the 2” Gallium Nitride µLED wafer. (b)The square with ‘µLEDs’ denotes the 90 x 90 micro-LED arrays for bonding to the CMOS. It is possible to create 12 on a 2” wafer. The other structures are a test and alignment structures. (c) SEM micrograph of an individual µLED (d) Light photograph of an individual µLED](image)

![Fig. 9 shows a 90 x 90 array of solder balls deposited on a flat silicon wafer on a pitch of 80 µm. This is the minimum pitch that can be achieved with the 50 µm diameter solder spheres, without defects (missing spheres, or double-spheres). Because the CMOS chip had a non-flat surface topography, some neighboring solder spheres tended to form double-spheres, which had to be manually removed prior to flip-chip. To avoid this tedious work, we decided to populate every second bondpad giving us a display with 4050 pixels on an 113µm pitch. The automatic solder bumping could be completed in a time of approximately 40 minutes per chip. After solder deposition, the LED array with matching bondpads to the bondpads on the CMOS chip was aligned in a FineTech flip-chip bonding machine, and brought into contact with the CMOS chip, as illustrated in Fig. 8(d). A bonding force of 5N was applied for the initial contact. This force was then removed and the assembly was heated to ~ 250 °C for the solder reflow.](image)
D. External control system

To allow command from a PC, we developed a control system using a Coldfire microcontroller MCF52559 from Freescale. The commands or images are sent to the microcontroller from the PC through the USB interface. Then, the controller interprets the received command to the 4-wire interface and inserts the additional command bit to the data frame. The microcontroller USB interface is based on the event-handler to efficiently use the USB interface. Then, the rest of the code is optimized for maximizing the communication speed with the matrix. After sending the data to the µLED matrix, the controller sends acknowledge to the computer for receiving any new commands in the stack of the computer.

V. RESULTS

To characterize the electrical and illumination efficiency of the µLED matrix, an optoelectronic testing rig was built which can be seen in Fig. 10. The chip was controlled via a Coldfire microcontroller, and voltage supply and current consumption measurements were performed using a Keithley 2612B Source Measure Unit. Optical emission was measured using a UV-818 photodiode from Newport. This had a 1cm diameter and was thus able to capture a significant portion of the light from the 8mm µLED.

Thermal measurements were performed using an IR camera OPTPI16048T900 from Optris PI is used to monitor and record the chip temperature. The connection diagram of the test platform is depicted in Fig. 10(a). Measurements were performed in a dark box, created from an adapted atomic force microscope housing. The light sensor was placed directly on the chip surface to measure the light intensity. In this form, most of the light was captured within the emission arc of the LEDs.

Although only a limited number of chips were bonded, we did not notice any adverse ESD events. i.e. the chips worked after post-processing.

In addition, different images are sent to the matrix as illustrated in Fig. 11. There was only a single pixel defect on this array. The operational objective for this matrix was to achieve:

- Each image requires 6 bits of PWM intensity modulation
- This gives an operating frequency of 13MHz.

Fig 11 (left) shows is an image created without correction. As can be seen, a mismatch in the impedances of the contacts results in a variance of the output image. These can be corrected using pulse width modulation protocols as seen on the right. The main limitation on speed is the speed of the microcontroller unit. We utilized a bit-banging method to create the communication protocol rather than a dedicated video stream. The measured current consumption due to the switching activities of the CMOS circuits is shown in Fig. 12. The static current floor is 1.3 mA which is mainly because of the pad ring and corresponds to simulation results.

(a)
(b)
(c)
(d)
Fig. 8 LED soldering steps (a) The first step which consists of preparing/cleaning the CMOS active area, (b) Second step is to deposit a barrier layer, then gold onto the surface contact pads. (c) Depositing the solder balls using Pactech machine, (d) Flip-chip bonding using heat and pressure step.

Fig. 9 (a) a photograph of the CMOS die with insert showing bondpad arrangement (b) solder bumps on the CMOS die where the zoomed subfigure shows the quality of the bonding process (c) The µLEDs after bonding to the wafer using the automatic pump machine.
The measured dynamic power consumption also corresponds to simulation results from Cadence – and scales with is $6 \mu A/Hz$. We believe both the static and dynamic currents of the circuits are acceptable given an overall target of around 500mW. We expect the µLEDs to be the main consumer of power.

The matrix LEDs are controllable from two sources: Locally by using pulse width modulation and globally, by modifying the drive voltage. As the control transistor is a pMOS, modifying the drive voltage changes the source voltage and thus the gate-source voltage $V_{gs}$ driving the drive transistor. Furthermore, if we consider Fig 13(a), we can see a load line plot between the properties of the drive transistor and the µLED. The intersection between the curves provides the voltage drop across the µLED for different drive voltages. The maximum current consumed by individual µLEDs is illustrated in Fig. 13(a).

These are for drive voltages of 5V. The maximum current is 2.5mA. The average value of the current consumption per µLED is about 0.4mA and consequently, the average efficiency per LED is 0.7% as tabulated in Table III. Another way of exploring this variation is to look at the variance in IV curves that can be seen in 13(b). In this case, the LED drive voltage and the Vdd of the control circuitry are connected, so changing the voltage also affects the $V_{gs}$ of the transistor.
Fig. 12 The measured dynamic power consumption of the electronic circuits during the matrix update at a supply voltage of 5V and switching frequency of 2.9MHz. The DC current consumption is 1.3mA due to the ESD pads.

Fig. 13 (a) Driver PMOS transistor load line with the measured LED current, (b) the IV curve for different LEDs on the matrix to show the variance in the threshold voltage due to bonding. Note in this case the drive voltage is Vdd_LED. Changing this also affects Vgs, so the LED response is a combination of the transistor (triode) and diode response.

However, the important point is the variation in effective turn-on voltage. This can be explained by variance in the resistance of the contact between the CMOS and the µLED as between a few hundred ohms to 1KΩ.

The illumination of each pixel was measured to determine the mismatch between the µLEDs and driving circuits. The average illumination per pixel is 8µW as shown in the distribution of the readings in Fig. 15. The area of each µLED is 314µm². So the average emittance per µLED is 25.3mW/mm². This is significantly beyond our minimum requirement. The maximum and minimum measured illumination power for the pixels are 42.6µW (135mW/mm²) and 1µW (3mW/mm²) respectively. With improved bonding technique, resistance would be reduced, and thus pixel emittance distribution would center tightly around the maximum emittance.

It should be noted, the µLEDs are at a spacing of 80 µm. Thus if optics were used to spread the intensity over the whole 80 x 80 µm pixel [39] the maximum and average emittance would reduce to 6.6, 1.2 mW/mm² respectively. This is limited by the PacTech bonding technique. Our electronics can scale to 40x40um pixels by using under pad circuit techniques. In this case, the emittance would be improved 4x. However, in both cases, this is still within our desired range given our optical system.

We have used a µLED with a 20º emission arc as shown in Fig. 2. Therefore, the average radiance = 8 µW / 0.04 sr = 0.21mW/sr. For comparative purposes, this equates to 2.2 million cd/m². However, we do not feel cd/m² to be useful for use with channelrhodopsin as it has a different sensitivity profile to the human eye.

Figure 15 shows the variation of µLED emittance and efficiency at an operational Vdd_LED = 5V. The efficiency of a solitary µLED is around 3%, however, this is reduced due to the effect of the bonding resistance and the voltage drop across the transistor. The maximum operational efficiency is 1.2% and average operational efficiency is 0.7%. A summary of the µLED test results is listed in Table III.

Across the whole matrix array, the maximum generated light power is 6.9mW at a supply voltage of 5V and power consumption of 1.99W. The illumination of the matrix increases with the voltage, the matrix efficiency reaches to the maximum value at VLED =3.3V. After this, the efficiency decreases to the value of 0.35% at LED voltage of 5V as shown in Fig. 16. This is partially due to the resistive effects of the contacts and partially due to the effect of droop as the current density increases from 32mA/mm² (at 10µA) to 3184 mA/mm² (at 1mA). This can be seen in Fig. 3(b). The temperature response of the matrix...
was investigated by turning on the whole matrix at different voltages and at different times.

![Histogram distribution of the µLEDs illumination power and it illustrates the differences in the illuminated power between the µLEDs and these values should be used to create the matrix calibration file.](image)

**Table III** Summary of the illumination measurements and the efficiency at different conditions at LED supply voltage of 5V.

<table>
<thead>
<tr>
<th></th>
<th>Illumination Power</th>
<th>Efficiency %</th>
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<tbody>
<tr>
<td>Single LED</td>
<td>1µW</td>
<td>8µW</td>
</tr>
<tr>
<td>Single column</td>
<td>370µW</td>
<td>550µW</td>
</tr>
<tr>
<td>Single row</td>
<td>308µW</td>
<td>650µW</td>
</tr>
<tr>
<td>Whole matrix</td>
<td></td>
<td>6.9mW</td>
</tr>
</tbody>
</table>

![Gaussian distribution of the µLEDs efficiency with the LED average efficiency is 0.7% and the maximum obtained efficiency is 2.73% and this figure is used also to determine the matrix calibration file to get same illumination power from all the LEDs.](image)

Fig. 14 (a) Histogram distribution of the µLEDs illumination power and it illustrates the differences in the illuminated power between the µLEDs and these values should be used to create the matrix calibration file. (b) Histogram distribution of the µLEDs current consumption at LED voltage of 5V and it shows a big difference in the LEDs current consumption due to the LED mismatch which affects the efficiency of the matrix.

Fig. 15 Gaussian distribution of the µLEDs efficiency with the LED average efficiency is 0.7% and the maximum obtained efficiency is 2.73% and this figure is used also to determine the matrix calibration file to get same illumination power from all the LEDs.
This should represent the worst case condition. A thermal image of the matrix during operation is illustrated in Fig. 17. It should also be noted from the image that the surrounding temperature is significantly lower, so we do not expect there to be a significant thermal impact on a retinal prosthesis headset. In addition, there was no heatsinking applied to the CMOS-μLED chip, which would reduce any thermal effects. In the first case, the whole matrix was kept on for a period of 20 minutes to explore temperature rises. The temperature increase continued from 5 to 7 minutes depending on the LED voltage as shown in Fig 18. The matrix undergoes an initial sharp increase in temperature followed by saturation. We stopped the experiment at just under 45°C. Though we would expect the chip to be capable of cycling at a higher temperature as the melting point of the solder balls is 250°C. We monitored the matrix illumination and efficiency during the ON time to record the effect of the temperature increase on the μLED performance. The effect of the temperature increase in the μLED illumination is very small as illustrated in Fig 20. However, the matrix efficiency decreased slightly with time as depicted in Fig 21. This means that the LED current consumption increased with time due to the temperature increase. Although the efficiency decrease of the matrix is very small at LED supply of 3V and 3.5V, it is higher at the case of V\text{LED} = 4V because of the high temperature of the matrix in this case.

It is important to note here that, the measured efficiency at this experiment is same as that values given in Fig. 16(a) which ensures the accuracy of the experiments.
Fig. 18 Measured temperature over a long period of continuous and pulsed modes operation at different voltages and different pulse width and it shows that the matrix temperature saturates before 10 minutes of the operation depending on the applied voltage to the µLEDs while the temperature increase for the pulse mode is much smaller than the continuous mode.

The matrix was also tested under pulse mode by turning on the matrix for a certain period at a supply voltage of 5V. We used a 100msec ON/OFF cycle period with the pulse widths at 10msec and 20msec (i.e. 10%, 20% duty cycle) as depicted in Fig. 19. The experiment period for each case lasted 20 minutes. for a supply voltage of 5 V, the temperature of the matrix raised from 25°C to 35°C in 9 minutes. In comparison, a continuously on matrix required less than 6 minutes to raise the temperature from 25°C to 45°C at the same supply voltage, as shown in Fig. 18.

Pulsed operation reduces the average emittance proportional to the duty cycle, as illustrated in Fig. 20. There is no apparent change in efficiency over time for either continuous or pulsed operation as per Fig 21. Finally, the illumination intensity could be controlled by changing the pulse width which could be used to display a gray scale image on the µLED matrix.

VI. DISCUSSION

In this work, a high density µLED matrix has been implemented, fabricated and tested. The primary purpose of the matrix is to form part of an electronic headset for stimulating ChR-2 encoded retinal cells for the retinal prosthesis. Furthermore, it may be that a compact matrix of this form is potentially useful for neuroscientific studies requiring compact addressable illumination sources.

![Fig. 19. Measured current during pulsing the whole matrix with a different pulse width and a supply voltage of 5V and for the continuous operation with different voltages. It shows that the current consumption is stable through long period of operation](image)

![Fig. 20. Measured illumination during pulsing the whole matrix with a different pulse width and a supply voltage of 5V and for the continuous operation with different voltages. It shows that the illumination is stable through long period of operation](image)
Fig. 21 Measured efficiency over a long period of continuous operation at different voltages which shows that the efficiency is stable with time with very small decrease which could be ignored.

An illustrative diagram of for the retinal prosthetic configuration is given in Fig. 1. This would embed the emitter array into virtual reality optics within a wearable headset. We aim to follow up this work and explore the optical integration fully. Here we have focused on the opto-electronic and thermal performance of the high radiance display chip.

The matrix can be controlled in active matrix fashion by either updating pixel ON/OFF status using rastering or pixel addressing techniques. A simple comparison between the chip and previously proposed chips is shown in Table IV and compared to other recent work.

Our matrix occupies a larger area than the previous designs and also increases the LED resolution significantly compared to previously. For comparison, the latest matrix proposed by [46] contains only 400 pixels compared to 8100 pixels in this case. Consequently, as the resolution increases, improved visual information transfer can be achieved in addition to reduced emitter intensities. Both solitary LEDs and combined LED drive circuit suffer from reduced efficiency as the drive current density increases. Thus reduced individual emittance requirements and thus drive current densities to improve efficiency.

The matrix is designed to fit into a WFO5 virtual reality optical module from eMagin. This has an eye relief of 27mm which makes it very compact. It also has a stated optical throughput of 60%, making it very efficient.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Electronic circuit supply voltage</td>
<td>5V</td>
</tr>
<tr>
<td>Frame refresh rate</td>
<td>25 FPS</td>
</tr>
<tr>
<td>Size</td>
<td>8mm x 8mm</td>
</tr>
<tr>
<td>Number of µLED</td>
<td>8100 µLED</td>
</tr>
<tr>
<td>LED voltage</td>
<td>3 – 5V</td>
</tr>
<tr>
<td>Control mode</td>
<td>Long shift/pixel mode</td>
</tr>
<tr>
<td>Average µLED performance peak</td>
<td>25mW/mm²(0.21 mW/sr)</td>
</tr>
<tr>
<td>Estimated pixel irradiance on retina</td>
<td>1.4 mW/mm²</td>
</tr>
</tbody>
</table>

Table V Actual performance parameters of the µLED matrix which are obtained from the experimental work.
counteracted by the 9x irradiance increase due to minification of the image of the display onto the retinal target. Our micro-emitters are able to achieve a peak and average emittances of 135, 25 mW/mm² respectively. However, this reduces to 6.6, 1.3 mW/mm² if we divide the light over the whole 80x80um² area. We, therefore, expect the irradiance at the retina surface to be suitable optogenetic stimulus with a full dynamic range of frequency response. A summary of the measured parameters of the matrix is tabulated in Table V. These give the average results. The best pixel intensities have almost double the performance and we would expect manufacturing improvement to tune this further in time. We explored the thermal performance of the emitter chip under both continuous and pulsed operation without heat-sinking. We find operational temperatures to be less than 50°C. simple passive heat sinking would reduce this, but it does not significantly affect efficiency. For comparison, typical processor core temperatures on watches, smartphones, and tablets regularly reach up to 60°C. If the matrix was to have all pixels on fully and continuously, the expected operational power is around 2W. However, a more reasonable operational state would be between 1-10% duty cycle given that not all the pixels would be on, and there would be differences in stimulus intensity or frequency for those that are. Thus, the operational power would be less than a typical smartphone (0.5-3W). We, therefore, do not expect any adverse thermal problems when integrated into a headset as a whole. In contrast to electronic forms of a retinal prosthesis, in the optogenetic case, no implantable component is required. Rather, remaining cells in the retina are tuned to accept high radiance light from an external display. This means that the optoelectronics are effectively wearable technology, with consequently fewer problems related to device degradation. Contrarily, it should be noted that as the stimulator is now fixed with respect to the head and camera view, eye movements are no longer as effective as implantable variants with direct light sensing.

VII. CONCLUSION

The design and the performance of a high dense µLED matrix are presented in this work. The matrix contains 8100 µLED pixels. Each pixel has its own memory cell to avoid rastering mode in the matrix control. Dynamic and static power consumption are measured and the values are very close to the simulation results. In addition, the average efficiency of the µLEDs was measured to be 0.7% which is an acceptable value for the GaN LEDs. Also, the temperature performance of the matrix is monitored and the matrix proved to be stable in the temperature response. Finally, the generated light intensity is enough to stimulate the ChR-2 from outside the human eye. Which means surgical operation could be avoided by using the proposed matrix for neuron stimulation.

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References


