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Fast GaN μ LED Pixel for Visible Light Communication Matrix Emitter.

Abstract—Gallium nitride (GaN) based LEDs are known for their high brightness and their high-speed commutation capability. Not surprisingly, GaN μ LEDs are often used in LED based visible light communication (VLC) systems, due to the large modulation bandwidth they can offer. Although VLC emitter are commonly built with a single LED, using a matrix of μ LED as the light source can have some advantages as higher linearity. In this paper, the design of a fast GaN μ LED pixel driver dedicated to matrix emitters is discussed.

Index Terms—VLC, μ LED, Pixel, Driver, Analog, CMOS, GaN.

I. INTRODUCTION

VLC has recently attracted a lot of interest as a new method to operate high data rate transmission [1]. The increase in data volumes, associated to the limited available Radio Frequency resources, has indeed drawn attention to visible light as an alternative data transmission medium. Visible light based telecommunication networks are by definition using some kind of VLC techniques to transmit data.

Achieving high modulation rate implies using a light source with a large electro-optical bandwidth. Thanks to its ability to withstand high current density, and the positive impact of such a current on modulation bandwidth [2], GaN based μ LEDs appear to be the best suited LEDs for this kind of application. Among the different possible modulation schemes, the one commonly used to achieve high data rate transmissions is orthogonal frequency-division multiplexing (OFDM), implemented with a single LED, driven with an analog signal [3], [4]. In these systems, data streams are transmitted on several subcarriers distributed in the signal bandwidth, producing a noise like signal used to modulate the light source intensity. Although the analog driving of a single LED was successfully used to build high data rate VLC emitters, the implementations reported in the literature are often complex and cumbersome [4]. Moreover, given the nonlinear electro-optical characteristic of the LEDs and the high peak to average power ratio of OFDM signal, distortion issues may arise. Limited power efficiency of fast analog drivers, and signal nonlinearity, are seen as possible shortcomings of single LED VLC emitters [5], [6].

Even though they are less common, some VLC emitters based on a group of on/off driven LEDs are proposed in the literature [5], [7]. To this day, relatively low data rate transmissions were demonstrated with this kind of emitter in comparison to single LED ones. Nevertheless, ON/OFF multi LEDs emitters offer better linearity than single LED ones, and do not require

analog drivers [5]. In this paper, we discuss the design of a LED driver circuit dedicated to one of these emitters.

II. CASE STUDY

This work was conducted given the following case study: a 11 bits digital to light (DTL) VLC emitter, based on a matrix of 32×64 pixels. Each pixel contains 6 LEDs at a $9.5\mu\text{m}$ pitch, thus, the driving pixel we have to design has a maximum size of $19\mu\text{m} \times 28.5\mu\text{m}$. As micro Display circuits, this CMOS driver based array will be stacked with the GaN LEDs array through dedicated post process after fabrication. This type of emitter contains 2^{nb} pixels, with nb the number of bits on which the input signal is encoded. Each pixel can either be turned ON to generate a quantity of light corresponding to 1 LSB, or turned OFF.

The LEDs to be driven are simulated with a static model, based on the results of $10\mu\text{m}$ GaN LEDs characterization, which characteristic is illustrated in Figure 1. This static model represents the LEDs junction. The current going through it is responsible of light generation. It is connected in parallel to a 85fF capacitor representing the dynamic behavior of the device. Finally, the μ LEDs manufacturing technic that is used imposes a common cathode for all LEDs of the matrix, thus forcing the driving to be done from the anode.

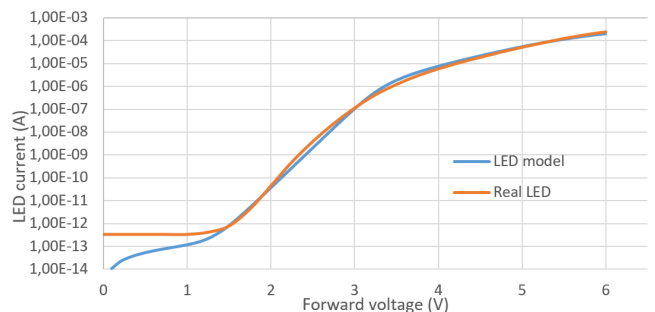


Fig. 1. Characteristic of the static μ LED model.

III. PROPOSED PIXEL

The proposed pixel circuit's schematic is shown in Figure 2. Its operation can be described using the block diagram shown in Figure 3.

A. Basic principles

The proposed pixel circuit has to maintain its LEDs in one of the two possible states, ON or OFF, depending on the control signal state. In order to provide high signal modulation bandwidth, the transition from one state to the other needs to

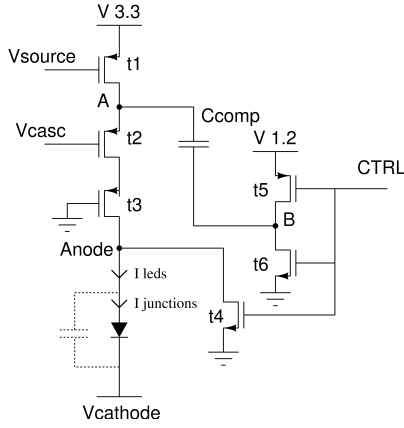


Fig. 2. Proposed circuit schematic.

be as fast as possible. Finally, this pixel is meant to be part of a matrix VLC emitter. Consequently, there is a need for high enough pixel-to-pixel uniformity, as it affects emitted signal quality.

Unlike other LED types, the GaN μ LEDs are expected to exhibit an important dispersion of their electrical characteristics. This is particularly true for the Brightness vs voltage one. As a result, applying a controlled voltage to the LEDs would not result in the same brightness for all the pixels. To avoid this issue, the pixel circuit drives the LEDs using a controlled current.

The LEDs need to operate under a high current density, both to ensure sufficient brightness, and to have a modulation bandwidth as large as possible [2]. Reaching a high current through the LEDs requires a relatively large voltage across the devices. The high current operation mitigates a part of the LED related bandwidth limitations. But we need a pulsed current injection to charge the LED's parasitic capacitor, and get a faster turn ON time.

In order to design a circuit taking into account these considerations, there is a need for compact and fast analog MOS, thus, smaller transistors are preferred. At the same time, because of a 2.25V dynamic required at the LED anode, and to keep transistors t1 and t2 in saturation, a voltage supply of 3.3V is required. For these reasons the driver is designed using a 130nm CMOS technology with 2.5V compliant IO transistors, while using a 3.3V power supply. This technology is chosen among other similar ones because of the low resistivity ultra-thick metal it offers, as this will help to mitigate voltage drop effects on power supply lines.

B. LED operating point

With the proposed pixel structure, only a part of the LEDs characteristic can be exploited, because the LED's anode voltage must stay between ground and the circuit power supply of 3.3V. In practice, the required voltage on transistors t1 and t2 to ensure their proper operation further reduces this range. The LEDs can be considered turned OFF when their current density is $5 \times 10^{-2} A/cm^2$ or less, which gives about 200nA for the entire pixel and a forward voltage of 2.75V. For the ON state, a pixel current of 384 μ A is chosen, which gives

a brightness of about $5 \times 10^5 cd/m^2$. This current requires a forward voltage of about 5V.

Consequently, a -2.75V is applied to the LEDs common cathode, and the pixel circuit will provide an anode voltage varying between 0V and 2.25V.

C. Circuit design

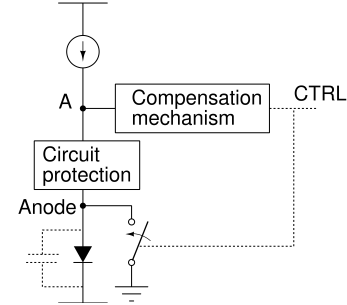


Fig. 3. Block diagram of the pixel.

1) *Current source*: The current source is meant to provide a constant 384 μ A current that sets the pixel brightness. Current programming techniques commonly used in display matrix, involve the memorization in the pixel of a new current value for each frame [8], [9]. This kind of control does not seem appropriate for communication dedicated fast operation. Current programming can indeed be a slow process. With the proposed architecture, implementation of current programming would require control voltages higher than 1.2V. When 1.2V is used for the matrix control signals. As there is no need in our application to provide different currents to different pixels, a simple current mirror with no memorization mechanism is used.

A diode connected MOS, associated to a current reference is placed on the matrix edge. This generates a steady gate voltage named Vsource with no settling time limitations, which is distributed to pixels in the matrix. In the driving circuit, this voltage is applied to the t1 transistor which acts as the pixel current source.

The resulting current mirror is sized with a W/L ratio which ensures a large $|V_{gs} - V_t|$, in order to maintain the generated current variation below 2% due to the IR drop in the power supply line. This sizing is done considering a power line supplying 32 pixels 28.5 μ m long, consuming 384 μ A each.

2) *Current boost mechanism*: Transistors t2, t4, t5, t6, and the compensation capacitor Ccomp form a current boost mechanism, which generates a short current pulse added to the constant current generated by t1. As reported by [10], such a current peak generated at the transition from OFF to ON state, allows a faster signal rise time.

In our case, this phenomenon is represented through the charge of the capacitor used to model the LED. Even if the current provided by the circuit changes instantaneously, it implies a modification of the voltage across the LED, which leads to a current going through the parasitic capacitor. As a result, the current going through the LED junction, which is the

current provided to the LED minus the one going through the capacitor, shows a slower evolution. At the turn ON time, the current boost mechanism provides an extra current, which would ideally correspond to the current going through the parasitic capacitor, leaving the entire current provided by the source to the LED junction.

The injection mechanism uses the inverter formed by transistors t_5 and t_6 to control this mechanism. t_6 is sized so that it won't be the element limiting the current during the capacitor charge, and t_5 is sized so that the output of the inverter reaches 95% of its final voltage after 1ns. The sizing of t_2 is so it stays in saturation region while the pixel is either in ON or OFF state. This makes the transistor large enough that it does not appear worthwhile to reduce the current peak duration by using an even larger transistor.

The inverter is controlled directly by the CTRL signal, to apply a rising voltage step to node B in Figure 2 when the pixel is turned ON. Node A, at the other end of the capacitor, is maintained at a constant voltage by t_2 , and current flows through the capacitor until an electric charge Q_{comp} has been injected.

Assuming the current injection is completed in a very short duration of time, we consider that the pixel's static current contribution to the parasitic capacitor charge is negligible. Then the value C_{comp} is chosen so the injected charge is equal to the one required by the parasitic capacitor to charge up. Thus $C_{comp} = C_{led} * \Delta V_{led} / 1.2 = 960 fF$.

However, simulation shows that the static current contribution to the parasitic capacitor charge is not negligible. Figure 4 shows the impact of C_{comp} value on the current going through the LED junction during the turn ON phase. An insufficient compensation leads to a long turn ON phase. While a too large compensation capacitor induces an overshoot before the pixel reaches a steady state. Tuning of C_{comp} to a value of 860fF allows the correction of the overshoot.

After a current injection was performed, the capacitor needs to be recharged for a future use. When the pixel is turned off, transistor t_6 applies a falling voltage step to the compensation capacitor at node B. A similar falling step is then observed on node A, which results in the current stopping to flow through the t_2 cascode transistor. The compensation capacitor is then charged through a constant current provided by t_1 , until the voltage at node A becomes high enough that t_2 turns ON again. As the capacitor is charged by the constant 384 μ A current provided by t_1 , the time needed to complete the charge can be estimated as $T_{charge} = C_{comp} * \Delta V_{comp} / I_{pix}$.

3) *Circuit protection*: t_3 PMOS is used as a protection transistor, preventing t_2 from being exposed to more than 2.5V. The voltage at node A is about 2.7V during steady state operation, and even greater during transition between OFF and ON pixel states. Without t_3 , the transistor would thus be exposed to more than its maximum 2.5V when the LEDs anode voltage is 0V as the pixel is OFF.

t_3 is sized so it operates in linear region during pixel ON state due to its high gate to source voltage, and presents a source-drain voltage under 40mV. When the pixel is OFF, the

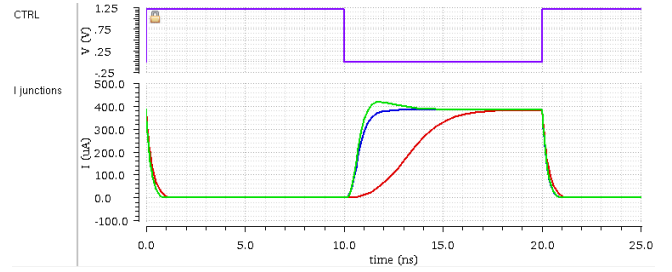


Fig. 4. LEDs junction current with $C_{comp}=0$ (red), 860fF (blue), 960fF (green).

protection transistor maintains a source-drain voltage of about 900mV, thus ensuring t_2 operates under a safe voltage.

4) *Turn off mechanism*: The LEDs are turned OFF by the action of the t_4 NMOS. This transistor, when ON, discharges the LED's parasitic capacitor much faster than it would be through the LED junction, by pulling anode voltage to the ground. t_4 also provides an alternate path for the constant current generated by t_1 when it is not absorbed by the compensation capacitor's charge, allowing the LED to stay OFF. Aside from discharging the parasitic capacitor, t_4 prevents the anode voltage from decreasing below 0V when the pixel is OFF. There is not much constraint on t_4 's sizing, it simply needs to be large enough that only a negligible drain-source voltage results from t_1 generated current going through.

D. Global operation

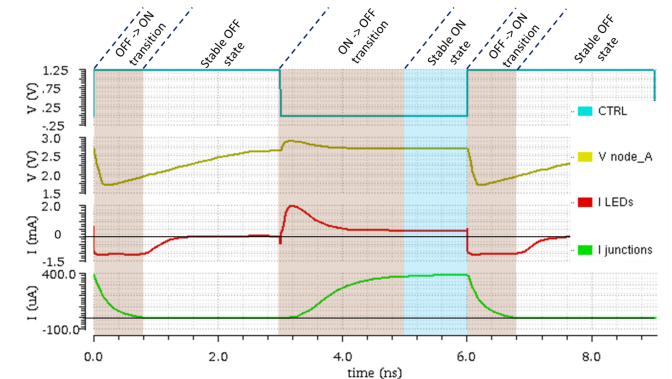


Fig. 5. simulation of the pixel operation.

The entire pixel operation is controlled by the CTRL signal. The LED turns OFF when CTRL is high, and ON when CTRL is low. Figure 5 shows pixel operation, when alternating ON and OFF state every 3ns. The 3ns period corresponds to the time needed by Compensation capacitor to be ready for the next current injection. This simulation shows the large current peak injected through the LED when it turns ON, while the current through the junction, which correlates with emitted light intensity, slowly establishes.

IV. LAYOUT

Figure 6 shows a layout of the proposed pixel. The largest device in the circuit is the compensation capacitor. It is implemented with a MOS capacitor, and marked C_{comp} on Figure 6. MOS capacitor is used for its relatively high density, and

because the circuit operation doesn't suffer from its voltage dependent capacity thanks to the way it uses it.

On the center of the layout, the red rectangle surrounds logic gates used to generate the CTRL signal, which is applied to t4, t5, and t6. For this example, a simple pixel control scheme similar to what is proposed in [11] is assumed. One signal per row and per column is distributed through the matrix. Each pixel generates its own control signal $CTRL = R + (R_{-1} \cdot C)$, with C the column signal, R and R_{-1} the row and previous row signals. With a view to the implementation in a matrix, V_{source} and V_{casc} as well as the row control signals are distributed via horizontal metal lines running through the entire pixel. Power supplies and column control signals are also distributed with vertical metal lines running through the entire circuit, although the top 4 metal layers are not displayed on Figure 6 for the sake of readability.

3.3V power supply is distributed with two lines $3\mu\text{m}$ wide, made of thick metal. When supplying power to a column of the described pixel, IR drop at the last pixel is limited to 5.3mV. The other power supply lines are made of finer metals with larger resistivity, as the IR drop on those is less critical for the circuit operation.

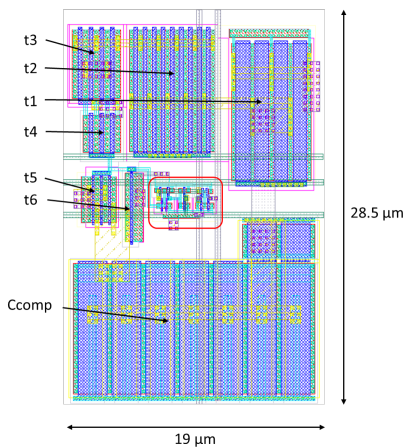


Fig. 6. Pixel circuit layout.

V. DISCUSSION

The proposed pixel circuit can display a new frame every 3ns. This corresponds to a framerate of 333 MHz. Given that each frame is coded on 11 bits, the transmitted signal bandwidth is about 3.66 Gb/s. In Table I simulation results of our driver pixel, which is fully integrated in a standard CMOS analog technology, offers high signal resolution, and competitive data rate, is compared to other existing solutions. For all multi LEDs solutions, in order to compare hardware performances and not modulation techniques, the considered data rate is frame rate times resolution instead of the effective transmission bit rate. The operation frequency of our pixel is mainly dictated by the compensation capacitor charging time, which imposes a 3ns long OFF state to ensure the next pixel turn ON can be completed in 2ns. Faster turn ON might be obtained by sizing up some of the components, mainly t5, Ccomp, and t2, but this would imply both a larger

	Data rate	integrated	signal resolution
This work	3.66 Gb/s	Yes	11 bits
Mono LED emitter [4]	7.91 Gb/s	No	10 bits
Multi LEDs [5]	150 Mb/s	No	6 bits
Multi LEDs [12]	800 Mb/s	yes	4 bits

TABLE I
COMPARISON BETWEEN VLC TRANSMITTERS.

silicon footprint, and longer mandatory OFF state duration. Consequently, the maximum operation frequency would not benefit from such a modification.

The part of the design related to the generation of CTRL signal may be modified to accommodate for a different kind of matrix level pixel control mechanism. Study of different possible pixel control schemes is ongoing work. A specific control mechanism, which take advantage of the aforementioned modified sizing for faster turn ON time is currently under study.

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