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Structure of a LIFI Dedicated Binary Pixel Array.

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Abstract—In recent years, visible light communication (VLC) have attracted a lot of attention as the key component of LIFI networks. Alongside complex and cumbersome mono LED implementations, which are used in labs to achieve extremely high data rate transmissions, slower but much more compact matrix emitters are found in the literature. In this paper, we discuss the choice of matrix architecture for data distribution and transmitter operation scheme.

Index Terms—VLC, μ LED, Pixel, Driver, GaN, Matrix, Data transmission.

I. INTRODUCTION

The constant increase of data generation and transmission, associated to the limited available radio frequency (RF) spectrum, make the implementation of new wireless links increasingly more difficult. Visible light communication (VLC) could be a new mean of wireless and high throughput data transmission. Consequently, VLC has earned a lot of interest during the past years, as a complementary data link to RF based ones [1].

VLC emitters generate an optical signal of variable power, and the light intensity is used to code the data to send. High data rate transmission requires the use of some 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 are well suited for this kind of application.

Modulation technics used by such transmitters can be relatively simple ones, such as OOK or PAM [3]. More complex modulations derived from typical RF modulations such as QAM and OFDM can also be used [4], [5]. OFDM proved to be an effective modulation technique, as it was used for what is, to the author's knowledge, the highest data rate transmissions demonstrated with VLC transmitters [6].

These fast data transmissions were achieved with single LED transmitters. The LED is supplied with a variable electric current, controlling the emitted signal's intensity. With OFDM modulation, data streams are transmitted on several subcarriers distributed in the signal bandwidth, producing a noise like signal with a high peak to average power ratio. Nonlinear electro optical characteristic of the LEDs and fast analog drivers, associated to such signal can lead to distortion issues [7], [8]. Moreover, reported implementations of this kind of emitter are often cumbersome, and use complex lab equipment.

Even though they currently offer 1 to 2 orders of magnitude lower data rate, some VLC emitters based on multiple binary driven LEDs are proposed in the literature [7], [9]. In such transmitter, each LED is either ON or OFF, and the signal

intensity is set by modifying the number of LEDs to be turned ON, rather than modifying their operating point. These emitters do not suffer the same shortcomings as single LED ones, as they do not involve any analog modulation. Although they have a much more compact implementation, they generate a lower resolution optical signal (generally less than 8 bits) because of a reduced number of LEDs.

In a previous work, we have discussed the design of a pixel driver circuit, dedicated to this kind of VLC emitter [10]. In this paper, we report the first design study on a fully integrated and high resolution (10 bits), multi LEDs VLC emitter. This work focuses on the organization of such pixel array, in terms of data distribution and choice of the LEDs to be turned ON.

II. USED PIXEL

The requirements for a pixel used in a VLC matrix are different from those for the pixels used in a typical display matrix. VLC matrix have a much lower resolution (1024 pixels for 10 bits transmission), but they need a much higher frame rate, in order to achieve significant data rate transmission. This study is conducted assuming each pixel is made of a GaN LED associated to a driving circuit as presented by Figure 1, and further described in our previous work [10].

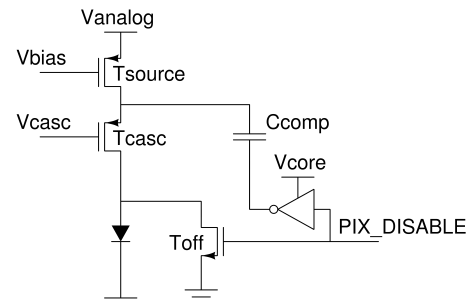


Fig. 1. Pixel driver circuit.

A. Operation principle

A current source implemented with T_{source} sets the operating point of the LED when the pixel is activated. This current source is based on a current mirror, with a current reference shared by several pixels, located on the edge of the matrix. The signal $PIX_DISABLE$ is used to control the pixel state. When $PIX_DISABLE = '1'$, T_{off} is ON and forces the LED anode to GND, thus preventing light emission. When $PIX_DISABLE = '0'$, T_{off} is disable and the current generated by T_{source} flows through the LED. This implies

a constant current consumption on V_{analog} independent of the pixel state. Thanks to this constant current consumption, voltage drop on power supply lines (IR drop) follows a known pattern, and is easier to compensate. Transition from '1' to '0' of PIX_DISABLE induces a charge injection through the C_{comp} capacitor. The resulting current peaking mechanism shorten the pixel turn ON phase [11], to about 3ns in this design.

B. Circuit limitations

Because of the expected high-speed operation, the current source is not implemented with in-pixel biasing memorization, as is typical for low frequency display oriented pixels. The current mirror used instead is particularly sensitive to differences between power supply voltage seen by pixels and the current reference.

The pixel circuit does not contain any internal mechanism to ensure synchronization with the rest of the matrix. Display dedicated matrix often use rolling shutter operation, in which data and gate voltage are distributed to one pixel row after the other, and have no need for synchronous pixel operation. However, rolling shutter operation is not acceptable for high-speed VLC operation, as it would imply temporal overlap of successive symbols. Consequently, the delay of PIX_DISABLE signal must be similar for all pixels of the matrix to ensure quality of conversion between input signal and light signal intensity. This can be obtained by implementing a clock-tree like routing strategy for example.

The constant current consumption on V_{analog} induces a higher power consumption than a more traditional pixel. The charge injection mechanism can generate simultaneous peaks of current consumption on V_{core} , on all pixels of the array. Finally, the planar GaN LED technology used for this design is still non-mature, and experiences high variability.

III. DYNAMIC OPERATION

A. Inter symbol interferences

During high speed operation, transient variabilities arise, as the pixel behavior depends on its state at the previous symbol. Figure 2 illustrates this phenomenon, showing the light intensity generated by a simple pixel receiving the bits sequence "01100". This sequence (resulting from the display of five successive input codes) contains all possible state successions. Because of the settling time, a steady state pixel illumination will differ from the one of a pixel changing state between two symbols. From the modulation perspective, transient errors depending on previous state are interpreted as inter symbol interferences (ISI) [12]. As any kind of interferences ISI have a negative effect on transmission performance, and shall be minimized when possible. Although the pixel driver is designed to minimize the settling duration, interferences are still to be expected between successive symbols. As illustrated in Figure 2, when PIX_DISABLE switches from '0' to '1', the pixel settling time lasts only for a fraction of the symbol duration, thus the transient error can be neglected for pixel OFF state, and mainly exist on ON state. Asymmetry between

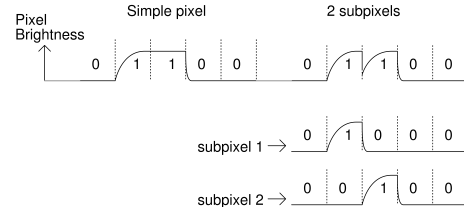


Fig. 2. Signal from single pixel with ISI, and alternative two subpixels option.

the rising and falling edges of the light signal comes from the difference between the mechanisms used to turn the LEDs ON and OFF. This is discussed in more details in our previous work on the pixel driver circuit [10].

As the ISI is mainly due to the difference of pixel behavior between "11" and "01" transitions, preventing the "11" transition to happen should greatly reduce ISI. Consequently we propose to use pixels made of two subpixels as shown in Figure 3, and adopt a return-to-zero operation for those subpixels. As shown in Figure 2 the two subpixels are al-

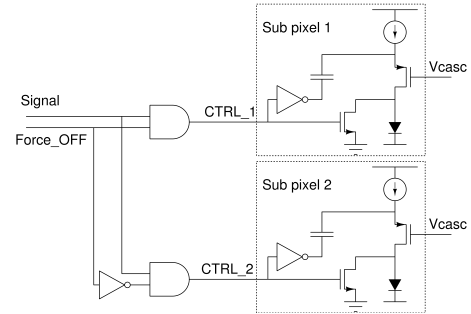


Fig. 3. Pixel made from two subpixels, with CTRL signal generator.

ternatively forced in OFF state, or controlled by the input signal. With this operation, no subpixel can experience a 1 to 1 transition, as a "11" sequence on a pixel will result in one subpixel displaying the first 1 then turning OFF, while the second subpixel is OFF then turns ON. Double subpixels structure doesn't prevent settling related signal non-ideality, but makes it consistent, thus easier to predict and take into account at signal reception.

Such double subpixels are controlled by a simple in-pixel combinatory logic. This logic uses "Signal" and "Force_OFF", which is common for all the pixels, generate a control signal for each subpixel.

B. Power supply distribution

Synchronous operation of all the pixels raises the concern of current peaks on power supply. Thanks to the pixels state-independent power consumption on V_{analog} , this voltage stays theoretically constant over time. On a real circuit, small variations are expected because of capacitive coupling between the power supply line and other nets of the pixels. V_{core} power supply on the other hand, experiences current peaks when pixels switch from OFF to ON state. To evaluate the resulting voltage fluctuation, a 10 bits transmitter is simulated, assuming

the double subpixels structure as described in III-A is used. This correspond to a 32 x 32 array of 38 μm x 28.5 μm pixels, as each pixel contains two side by side 19 μm x 28.5 μm pixel circuits. In simulation, the array is powered from the 6 following points: the four corners, center top, and center bottom. In the worst case, on which all pixels are switching at the same time, an IR drop pattern covering 8 x 16 pixels is repeated on the entire array. Figure 4 displays the V_{core} voltage seen by the best and worst pixels (nearest and farthest from the power supply) of this repeated pattern. Despite the

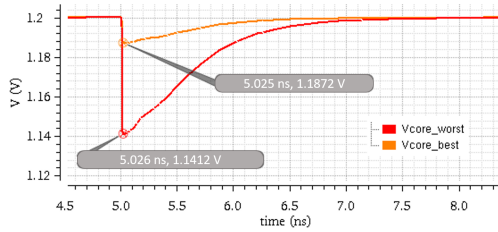


Fig. 4. Best and worst IR drop experiences on V_{core} .

synchronous operation of the array, reduced number of pixels and large power supply lines limit the voltage drop. The obtained drop is about 5% of the nominal voltage, which is generally deemed acceptable for a digital power supply.

C. Frame rate enhancement strategy

The current peaking mechanism built into the pixel improves the turn ON settling time. The capacitor used in this mechanism needs to charge up in between current peak generations. This charge is done when the pixel is turned OFF, with the current provided by T_{source} . This capacitor charge, imposing a minimum duration of the pixel OFF state, is currently the limiting factor for increasing the matrix frame rate. To overcome this limitation and to allow operation of the matrix as fast as the pixel settling time allows, we propose to increase the current going through the pixel during OFF state. With the double subpixel structure described in III-A, the two subpixels can be provided with a different V_{bias} for current mirror biasing. Using two sets of V_{bias} for the two sets of subpixels, current source biasing can be increased during the forced OFF state. With this variable current value, capacitor charge is made faster, while maintaining the pixel circuit structure. At the pixel level total current consumption doesn't change between frames, thus a constant IR drop on the power supply is maintained.

IV. MATRIX ORGANISATION

In a VLC matrix, the number of active pixels determines light signal intensity, but the location of ON state pixels is not critical. In that regard, the studied VLC matrix is very similar to a current switching or current steering digital to analog converter (DAC), in which a series of current sources can be activated and have their current summed up to form the converter output. Each pixel of the matrix is similar to a unit current cell, and the light from all the pixels sums up to form the emitter output. Consequently, the VLC matrix can

be studied as a digital to light converter, and evaluated using classic DAC characteristics.

A. Weighted pixel groups

A first solution is to organize pixels into weighted groups, each associated to one bit of input signal. For a N bits input signal, each pixel group g_i with $i \in [0;N-1]$, contains 2^i pixel. Each bit b_i of the input signal controls the state of g_i . The generated light intensity is $L_{array} = \sum_{i=0}^{N-1} b_i * 2^i * L_{pix}$, with L_{pix} the light generated by one active pixel. Figure 5 illustrates groups sizes and typical locations on such matrix for a 6 bits transmitter. The use of weighted pixel groups

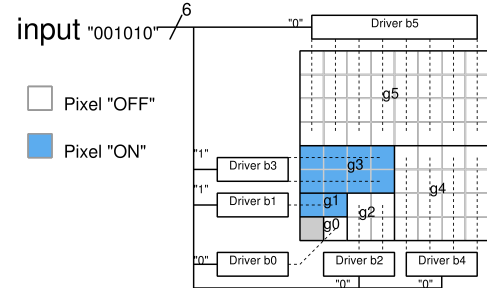


Fig. 5. Weighted pixel groups for 6 bits transmitter, and associated driving blocks, with "001010" code displayed.

allows for a very simple data distribution, as the input signal needs no transformation to directly control pixel groups. The reduced number of pixel groups enables distribution of a dedicated V_{bias} for each group, allowing matrix calibration to compensate for LEDs mismatch. Although such a calibration option seems interesting at first, it relies on using different LED operating points for different pixel groups, and the calibration may not stay correct through a large temperature range, or during ageing.

In a matrix with N pixel groups, PIX_DISABLE signals' loads differ a lot from each other, because of the important pixel number variation between groups. Consequently, attention must be payed to optimize signal synchronization, by choosing appropriate buffer fan-outs and digital cell delays.

The different pixel groups act as weighted light sources, and are functionally equivalent to the weighted current sources found on switching current DAC. Data conversion from digital to analog domain using weighted sources is fine when the sources are properly matched. However, given the important mismatch in planar GaN LED technology, differential non-linearity (DNL) can be seriously degraded. In some cases conversion can even become non-monotonic [13].

B. Independent pixels

Because of the aforementioned limitations of the weighted groups based structure, the use of independent pixels is preferred. With this organization, each pixel is a light source operating independently from the other ones. There is no association of a pixel with a particular bit of the input code. For any input code with an equivalent value n, the first n pixels of the matrix are active [13]. For independent operation,

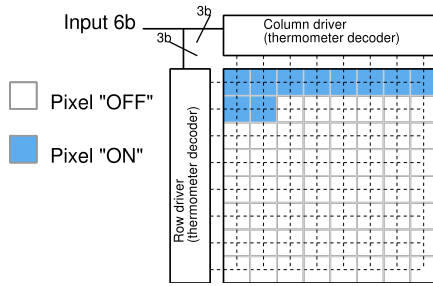


Fig. 6. 6 bits transmitter with independent pixels, and associated driving blocks, with "001010" code displayed.

each pixel needs its own control signal. Theoretically, these control signals can be generated from the input code using a simple binary to thermometer decoder, but this would not be a practical solution because of the large number of signals to generate. A more practical solution, as shown in Figure 6 is to use a thermometer decoding on the most significant bits of the input signal to generate one signal for each column, and a thermometer decoding of the other bits to generate one signal for each row of the matrix. Then, a combinatory logic decoder implemented in each pixel generates the $PIX_DISABLE$ signal based on column and row signals [14]. For a pixel on the n^{th} row and m^{th} column, with R and C respectively row and column signals: $PIX_DISABLE_{N,M} = R_n + R_{n-1} \cdot C_m$.

Although using independent pixels induces higher circuit complexity for control signals decoding, it offers several advantages over the use of weighted pixel groups. For any transition of the input code equivalent value from n to m , with m higher than n , all previously active pixels stay in this state and new ones are activated. Consequently, the generated light power increases, insuring a monotonic transfer function from input code to light signal, even with severe mismatch among the LEDs. Control signal distribution through entire rows and columns helps to balance data lines load. All pixel circuits can have the exact same layout, which is beneficial for matching. Figure 7 shows the integral non-linearity (INL) and DNL obtained with weighted pixel groups, and independent pixels. The simulation is done assuming a 10 bits matrix of double subpixels as described in III-A, with no LED mismatch. It only takes into account the brightness variability due to IR drop through the array, with the same V_{bias} provided to all pixels. The structure with independent pixels offers a lower DNL than the one with weighted pixel groups. Even though its maximum INL is higher, it evolves smoothly with the input code and can be compensated through signal predistortion, which is common in RF applications. Adding a random mismatch of $\pm 30\%$ at 3σ on the LEDs efficiency, the average linearity over 10 000 simulations is as follows: maximum INL = 1.78 LSB and maximum DNL = 1.09 LSB with weighted pixel groups, maximum INL = 1.74 LSB and maximum DNL = 0.14 LSB with independent pixels. Hence, aside from calibration capabilities, weighted pixel groups present no advantages over independent pixels structure, which ensures conversion monotonicity and uses the same layout for all pixels.

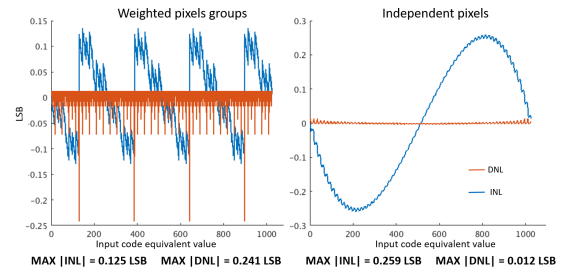


Fig. 7. INL and DNL a 10bits array, with the effect of IR drop.

V. CONCLUSION

In this work, we report on the use of two subpixels per pixel to mitigate ISI, and enhance pixel frame rate up to 333 MHz. We also use simulation to compare pixel arrays with independent pixels and weighted pixel groups. The former offers better conversion linearity when dispersed LEDs are used, and paves the way to an ultra compact and high resolution LED array based VLC circuit for LiFi networks.

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