Integrated driver with optical compensation for improved uniformity of emissive displays

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Abstract

Large area emissive displays have problems with non-uniform pixel characteristics and their individual ageing. A pixel integrated driver with pixel based optical feedback is presented to solve these problems. Photodetectors, optical feedback circuit and data handling capabilities are integrated in a high voltage CMOS technology.

1. Introduction

Emissive display technologies such as LED, OLED or CNT can be used for large area displays. However, non-uniformities between the different pixels as well as different individual ageing of the pixels make it hard to guarantee a uniform display.

In order to reduce the initial non-uniform light output, often only pixels with very similar characteristics are chosen, but ageing non-uniformities still remain. For some technologies, such as LED, the ageing curve is rather device independent and might be incorporated in the display driver. Other technologies such as CNT however, have different ageing properties for each pixel, and the ageing curve is not known in advance. A pixel based and in situ ageing compensation is necessary to preserve the uniformity of the display.

In this paper, a driver chip is presented that is mounted underneath a pixel or a small group of pixels. Integrated photodetectors provide an optical feedback signal which is used to compensate the individual ageing of each pixel at any given time by means of PWM driving. Each chip works on a stand alone basis and thus allows easily manipulated large area displays. A prototype ASIC has been designed in a 100V CMOS technology (I^2T100, ON semiconductor), thus proving the technique to be applicable no only to lower voltage technologies such as LED, but also high voltage technologies such as CNT.

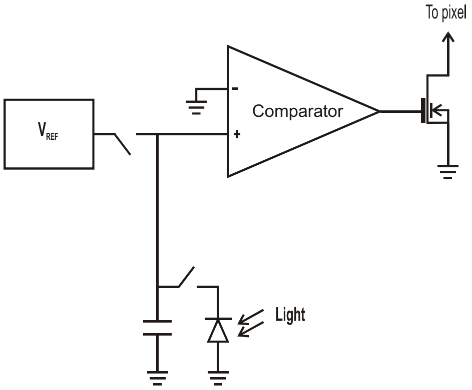

Fig. 1. Basic PWM principle

2. Principle of Operation

Figure 1 shows very simply how the PWM waveform is generated [1]. A capacitor is charged to a voltage V_{REF} and discharged with the photocurrent from a photodetector (photodiode or phototransistor). Thus, when the pixel gets dimmer due to ageing, it will produce a lower photocurrent and take a longer time to discharge the capacitor. This leads to a larger duty cycle and therefore the total amount of emitted light per frame will be constant. This is easily seen in following equation:

$$E(f) = p^i \cdot f \cdot \Delta t = p^i \cdot f \cdot \frac{C \cdot V_{REF}}{I_{ph}^i \cdot f}$$

$$= p^i \cdot \frac{C \cdot V_{REF}}{I_{ph}^i} = E_0$$

Where E is the total amount of emitted light energy which becomes independent of the brightness factor f of the pixel. p^i and I_{ph}^i are the initial power and photocurrent when no ageing has yet occurred. However there are some considerations:

1. All quantities in the above equation are unknown. The initial power of each pixel will be different, the value of an integrated capacitor in CMOS technology has only 20% accuracy and due to coupling differences between each pixel and the driver chip the initial photocurrent can widely vary. The photocurrent will also be different for each colour, as the spectral response varies.
2. If one would apply optical feedback on two nearby pixels, crosstalk can hardly be avoided. The light of one pixel will contribute to the photocurrent of another pixel, resulting in incorrect duty cycle adjustment.
3. Ambient light might contribute to the photocurrent and should be cancelled out. As light of the pixel must reach the driver chip, it might not always be possible to shield the driver chip from incident ambient light, again leading to an incorrect adjusted duty cycle.

The first problem can be solved if we calibrate the pixel with its driver chip. By measuring with an external photodiode and adjusting V_{REF}, the duty cycle of each pixel can be set so they all emit the same amount of optical energy.

If an initial power spread of $x\%$ is allowed and an ageing correction up till $y\%$ power loss should be possible, the full scale ratio over which V_{REF} should be adjustable is given by:

$$\frac{V_{REF,\max}}{V_{REF,\min}} = \frac{I_{\max}}{I_{\min}} \cdot \frac{(1-x)(1-y)}{(1+x)}$$

where I_{max} and I_{min} are the maximum and minimum expected photocurrents. The ratio between I_{max} and I_{min} is defined by x and y but also by the problems discussed above: technology uncertainties, coupling differences and spectral response ratio for different colours. This ratio is easily up to 50.

The resolution with which V_{REF} should be adjustable depends on the error in emitted optical energy ΔE allowed between the different pixels. However ΔE should always be less than half the energy of one grey value $E_{gr} = \frac{E_{frame}}{2^N - 1}$ in order to have a meaningful display, where N is the number of bits used to represent grayscales. For an 8 bit display, this means only a *0.2%* pixel output deviation. It can be calculated that a linear adjustment of V_{REF} needs a resolution n:

$$n \geq \log_2\left[\left(\frac{I_{\max}}{I_{\min}} \cdot \frac{(1-x)(1-y)}{(1+x)} + 1\right) \cdot \left(2^N - 1\right) + 1\right]$$

For an 8 bit display with $x=25\%$, $y=50\%$ *and* $I_{max}=50I_{min}$, we find a 12 bit adjustment is necessary!

The second problem implies that the feedback can not be done at the same time for all pixels, but should be carried out separately for nearby pixels and stored on chip. As the variations in output power only appear slowly in respect to the time it takes to refresh the stored feedback value, this does not mean system degradation. Also, a sampled feedback principle, allows one driver chip to correct more than one pixel as each value can be separately measured and stored on chip.

The third problem suggests that two measurements should be made: one where the pixel is off and only the ambient light contributes to the photocurrent and one where both ambient light and pixel light contribute. By subtracting both measurements, ambient light influence can be cancelled out.

Figure 2 represents the system design, as integrated on a prototype chip, which answers all considerations mentioned above. The next paragraphs will discuss this more complex system.

3. Sampling feedback necessity

In the second paragraph we showed that, with some considerations taken into account, optical feedback can be used to make all pixels emit the same optical energy per frame E_0 by changing the PWM duty cycle. However, if greyscaling is to be implemented, it must also be done by changing the duty cycle. This means a multiplication is needed in order to derive the correct duty cycle from both greyscale value and the optical correction factor:

$$\begin{aligned}\text{pixel on time} &= dc \cdot T_{frame} \\ &= \frac{\#greyvalue}{2^N - 1} \cdot \alpha_{ph} \cdot T_{frame}\end{aligned}$$

Where dc is the resulting duty cycle and α_{ph} the duty cycle adjustment factor coming from the optical feedback.

The resulting PWM waveform can be generated by directly changing the value of V_{REF}. However, as V_{REF} is already used to calibrate the pixel-driver entity, V_{REF} should be adjustable with the same precision as before, but now over a much wider range. A +20 bit resolution is necessary, only achievable with an oversampling DAC, thus massively complicating (and enlarging) the driver chip.

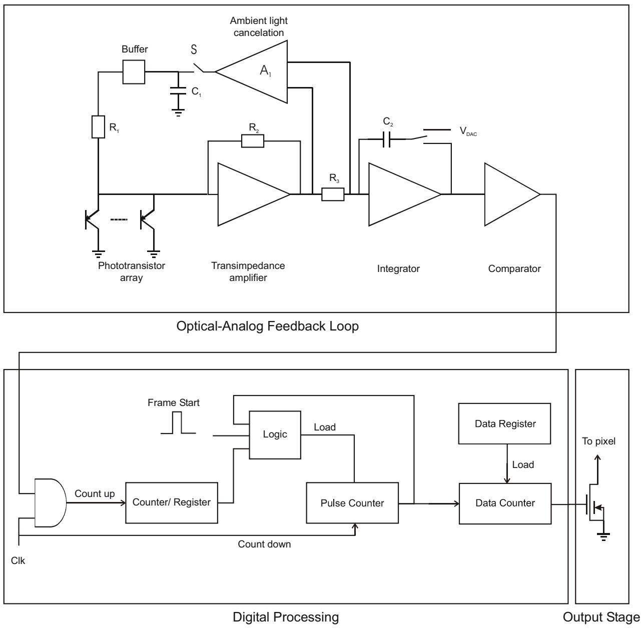

Fig. 2 Total feedback system with greyscale sampled optical feedback with ambient light correction

In [1] an easy solution is presented, which can also be seen in figure 2. The optical feedback loop (upper part of figure 2) is used to generate a duty cycle which is stored in a counter/register. This duty cycle is then multiplied by the greyscale value by means of two easily implemented counters: the duty cycle is "replayed" as many times as the greyscale value defines.

Mark that by storing the optical feedback duty cycle in a counter/register:

1. We obey to the second consideration as mentioned in the previous paragraph. The optical feedback loop can now work completely independent from the pixel driving PWM waveform generation.
2. This means that no timing constraints towards the optical feedback loop remain: the determination of α_{ph} can be done in whatever time frame the designer chooses, thus greatly reducing bandwidth requirements for the analog electronics!

4. Optical feedback with ambient light correction

The upper part of figure 2 represents the analog electronics used to define α_{ph}. Let us omit the ambient cancellation opamp, buffer, C_1 and R_1 at first. An integrated photodiode is used to measure the emitted light. To keep the voltage over the diode constant, a transimpedance amplifier holds the voltage. It is in our interest to choose this voltage high, as the higher this voltage, the wider the pn junction depletion region will be and the larger the generated photocurrent. This photocurrent will generate a voltage over R_2 and thus a current will flow through R_3, discharging capacitor C_2. The voltage over C_3, starting at V_{REF}, will decrease and flip the comparator, thus generating the correct PWM duty cycle.

To cancel out any ambient light during the measurement, we now take a look at the whole analog system: first, with the pixel off, switch S is closed. Ambient light (but also offsets of opamps, leakage currents,…) will generate a current through R_3, which is sensed by opamp A_1. This sensed voltage is used to change the current through R_1. If the gain of this feedback loop is sufficiently high, the voltage over R_2 will be brought to zero and the capacitor will not discharge.

Next, when switch S is opened, the current through R_1 is preserved because of C_1 and the buffer. When the pixel is turned on, both ambient light and pixel light will contribute to the photocurrent. However, the ambient light contribution is now compensated by the current through R_1, so the measured duty cycle will only depend on pixel-emitted light.

5. Photodetector and technology considerations

Previous paragraphs explained how integrated optical feedback can solve ageing problems and how this can be implemented in a driver chip. A key element is of course that this driver chip should be as small as possible for cost reasons. Therefore, we are limited in photodetector area, meaning small photocurrents are to be considered. Using ON semiconductors I^2T100 technology which is a *100V* – 0.7µm CMOS technology a photodiode of 0.25mm^2 using only CMOS layers as shown schematically in figure 3, gives a photocurrent of approximately *125nA @ 100µW/cm*^{2}.

As these small currents are expected, the analog electronics require very low noise circuits which results in larger chip area. More so two important considerations have been found from previous prototypes [1]:

1. As the photodetector is illuminated, photocurrent is generated in reverse biased pn junctions. However, on an integrated system, this means that all electronics are illuminated and photocurrents are generated in every device. Especially the low noise analog circuitry should therefore be shielded with metal at all time!
2. It is known [2],[3] that photocurrent consists of two major contributions: drift current, from electron-hole pairs generated within the depletion layer and diffusion current, originating from generated electron-hole pairs slowly diffusing toward the depletion layer. However, we have seen that photo generation as far as 100µm from the device, will contribute to the photocurrent if the device is not properly shielded. This also means great care in shielding the photodetectors from the digital and analog electronics should be taken since analog or digital signals can easily influence this diffusion current towards the photodetectors and thus the measured photocurrent! Generally in a p-epi process a p+ diffusion guard ring is advised as shown in figure 3. However, a p+ guard ring will only collect diffusing holes, while electrons are still free to diffuse towards the depletion layer and contribute to the photocurrent. In order to stop diffusing electrons, an additional n-type guard ring should be provided as shown in figure 3. Mind that the two parasitic photodiodes will not contribute to the photocurrent I_{ph}.

The use of a high voltage technology, necessary for the output stage in certain emissive display technologies (CNT, OLED,…). However, it also allows for improved photodetectors. High voltage technologies offer lower doped N+ and P+ regions, allowing for wider depletion regions and improved photoresponsivity, thus reducing the detector (and chip) size. Moreover, buried layers and deep n+ and p+ diffusions allow excellent shielding of the photodetectors from analog and digital circuitry.

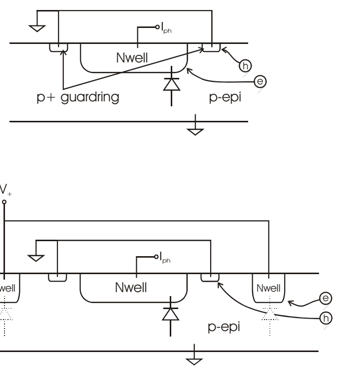

**Fig. 3 Guarding of a nwell/p-epi photodiode.
Above: normal p+ guardring
Under: additional nwell guardring**

4. Summary

A driver schematic was presented which allows for ageing correction of emissive displays. It was shown that in order to integrate optical feedback within the driver chip and use in a display, a sampled feedback is needed. By sampling we make sure no crosstalk between nearby pixels exists and allow one driver chip to drive and compensate multiple pixels. Furthermore, sampling allows for an easy digital approach towards greyscaling. It was shown that a correct ageing compensation must take ambient light into account and an integrated system schematic was presented and discussed. Design recommendations were given for integrated optoelectronics: special care must be taken to shield the photodetectors from other electronics. Advantages of the use of a HV technology were given.

5. References

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