Design of an Integrated OLED Driver for a Modular Large-Area Lighting System

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Abstract: - The concept of a flexible, large-area, OLED-based lighting system with a modular structure and built-in intelligent light management is introduced. The paper describes the design of a high-voltage integrated circuit for driving and controlling an individual OLED tile in this modular lighting system. The chip comprises a switching DC-DC buck converter for generating the OLED current and a sensitive analog feedback loop for adjusting the duty cycle of the converter's PWM control signal. The chip was designed in the 80V 0.35μm I3T80 technology of ON Semiconductor.

Key-Words: - OLED driver, lighting system, switching DC-DC converter, buck converter, PWM control, optical compensation, IC design, smart-power technology

1 Introduction

OLEDs (Organic Light-Emitting Diode) are paper-thin and lightweight opto-electronic devices consisting of organic materials that emit light in response to an electric current. They can be made on rigid glass substrates as well as on flexible foils, and have the attractive advantage of being areal emitters in contrast to inorganic LEDs that behave like point emitters. OLEDs consume up to 70% less energy compared to conventional light sources, thereby making OLED technology a prime candidate for the next generation of energy-saving lighting applications. However, before flexible large-area OLED lighting can be commercialized, more R&D is needed to solve some remaining challenges in different fields. This mainly concerns the driving electronics, power distribution, integration and miniaturization, as well as sensor-based human interface and application-specific intelligence. The research described in this paper tries to tackle some of these issues.

2 The IMOLA Concept

In October 2011, the research project IMOLA, acronym for "Intelligent light management for OLED-on-foil applications", was launched. This project, funded under the Seventh Framework Programme for ICT of the European Union, will run for 3 years and has the ultimate goal to develop an interactive, modular, flexible, large-area, OLED-based lighting system on low-cost foil with built-in intelligent light management. Possible future applications are widespread, with interesting examples like in-house wall and ceiling lighting, or automotive dome lighting. In these systems the light intensity can be controlled uniformly on the whole OLED panel, but due to the modular nature the brightness can also be adjusted locally at module-level. This enables advanced sensor-based features with pronounced human/ambient interaction capability: light on a ceiling or wall can follow the position of a person or mimic a person's gestures, or light can gradually move from east to west to create a kind of daylight experience. The possibilities are almost unlimited!

The basic IMOLA concept is illustrated in Fig.1. The large front panel contains a matrix of OLED tiles, each tile having a typical size of 5x5cm^2 or 10x10cm^2. The flexible back panel comprises all the electronics for driving and controlling the brightness of individual OLED tiles, i.e. one switching DC-DC converter chip and one embedded inductor per tile. The inductor is needed for the proper operation of the OLED driver chip. At the end of the process flow, the front and back panels are laminated together, using a combination of non-conductive structural adhesive for the mechanical stability and patterned isotropic conductive adhesive for the interconnection between the OLED electrodes and the electronics behind it. Apart from the driver chip and the embedded inductor, the back panel also carries the metal tracks for power distribution across the whole lighting system.

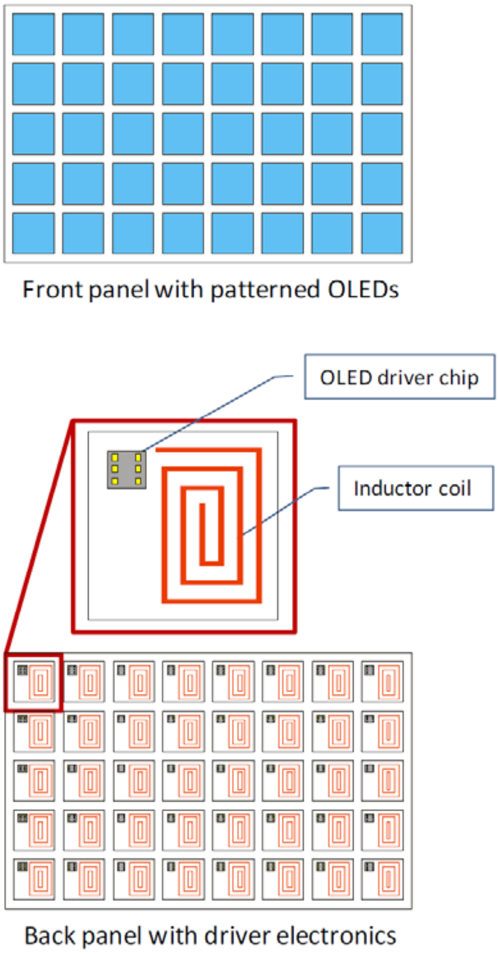

Fig.1: The basic IMOLA concept.

A 3D impression of this new concept, clearly identifying the main components of the modular lighting system, is shown in Fig.2.

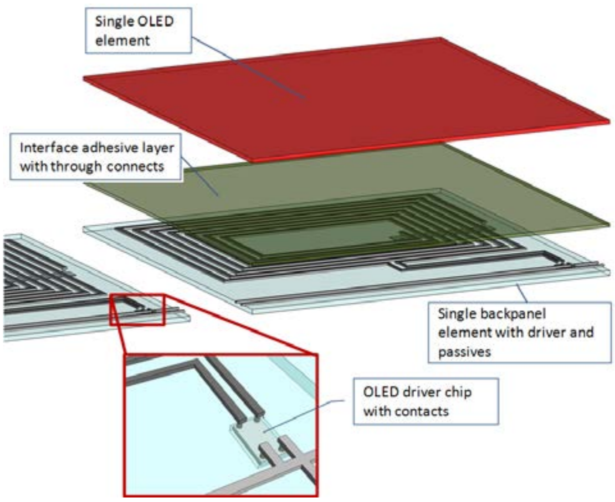

Fig.2: 3D impression of the IMOLA concept.

From an electrical point of view, the lighting system will look like in Fig.3. A central power converter transforms the main power supply (e.g. the 220V or 110V AC mains in case of a wall light) into an appropriate DC voltage that distributes the power across the whole back panel. This DC voltage level should be high enough to keep the conduction losses in the very thin power supply tracks of the back panel foil within reasonable limits. However, it shouldn't be too high either because of safety aspects and voltage restrictions of the back panel technology. A value of 40V seems an adequate trade-off between the different design criteria. Within each module, the OLED driver chip should down-convert this 40V DC voltage to a much lower level in the range from 5V to 10V for adjusting the OLED brightness. In order to maximize the power efficiency of the system, a switching DC-DC buck converter topology is chosen. The inductor, needed for proper converter operation, is a single-layer spiral metal coil embedded in the flexible back panel foil.

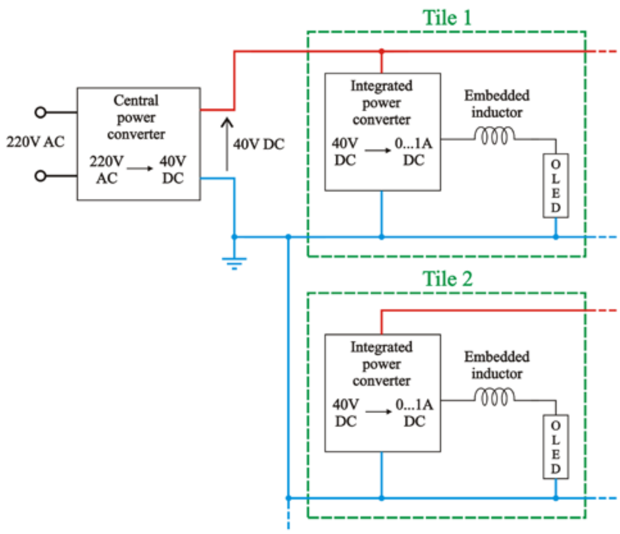

Fig.3: Electrical block diagram of the large-area OLED lighting system.

The modular nature is clearly a key feature of the proposed lighting system. It does not only allow individual OLED module brightness control to support human or ambient interaction based on integrated or centralized sensors, it also enables us to counter-act ageing or degradation effects in the OLED cells. Although OLED technology has improved significantly over the past years, long-term degradation is still a major concern and limits the lifetime of an OLED lighting system. The original modular structure of the proposed IMOLA concept is able to compensate those ageing effects on the basis of the optical feedback mechanism depicted in Fig.4.

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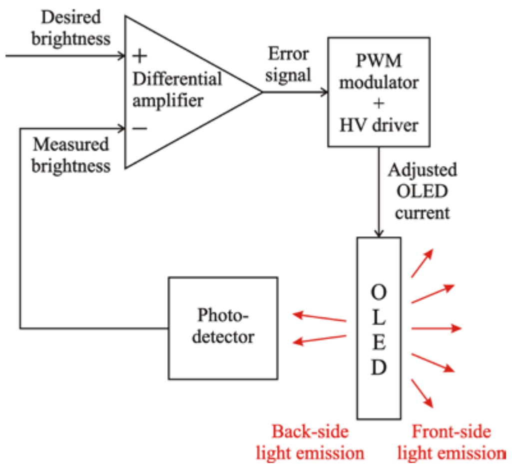

Fig.4: Optical feedback for automatic compensation of OLED degradation.

A photo-detector embedded in the back panel foil or integrated on the driver chip itself captures a fraction of the light emitted by the OLED tile. The measured OLED brightness is then compared to the desired brightness level, and the error signal from the differential amplifier is used to fine-tune the duty cycle of the PWM signal, thereby adjusting the OLED current. By doing so, the actual OLED brightness always equals the desired level, no matter the degree of OLED degradation. It is clear that this kind of optical calibration doesn't have to be done continuously but only once in a while.

It should be noted that this lighting system also needs some kind of data communication between a central control unit and the individual OLED tiles in order to control the luminance of all tiles, or between the OLED tiles themselves. It is the intention to use advanced PLC techniques (Power Line Communication) to transmit data (e.g. luminance data or integrated sensor data) across the 40V DC power supply track. This will reduce the complexity of the interconnection layout on the flexible back panel.

3 OLED Driver Design

The well-known architecture of a switching DC-DC buck converter is given in Fig.5. It consists of a PWM-driven high-side switch, a free-wheeling diode and a current-stabilizing inductor. The DC output voltage across the OLED is proportional to the duty cycle of the PWM signal, which enables us to control the OLED current. Note that the OLED current still exhibits a triangular fluctuation with an amplitude that is proportional to the DC supply voltage and inversely proportional to the inductance value and the PWM switching frequency.

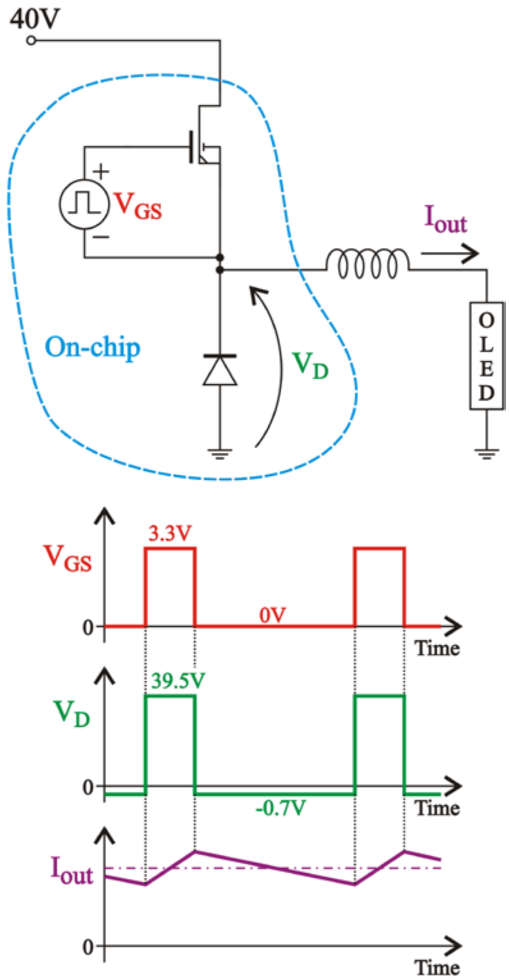

Fig.5: Basic DC-DC buck converter architecture.

As already stated before, the inductor of the switching DC-DC buck converter is a single-layer spiral metal (Cu or Al) coil embedded in the flexible back panel foil. Unfortunately, such an embedded inductor suffers from several parasitic effects. First of all, there is a considerable series resistance from the very long and very thin (order 50µm) Cu or Al track of the coil, producing additional conduction losses. Secondly, the very small distance between the coil and the OLED cathode generates significant parasitic capacitance between the coil and ground, resulting in increased switching losses in the converter and high-frequency resonance phenomena that weaken the current-stabilizing effect of the inductor. Finally, the proximity of the OLED cathode also reduces the coil's inductance by a factor of 5 due to the mirror effect in the conductive ground plane.

These parasitic effects were taken into account during the design of the OLED driver chip by adopting the simplified equivalent inductor model presented in Fig. 6.

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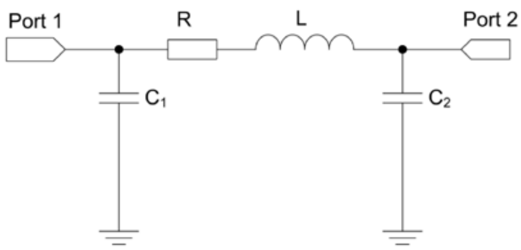

Fig.6: Simplified model of the embedded inductor.

Based on calculations and 3D EM simulations, the following target values for the model parameters seem realistic: an inductance L of 5µH (provided that the embedded inductor can occupy most of the tile area and that ferrite films are used to counter-act the mirror effect in the ground plane), a series resistance R of 1Ω, and parasitic ground capacitances C_1 and C_2 of about 50pF. Since the inductance that can be obtained for the given tile sizes is rather limited, very high switching frequencies are needed, in the range from 5MHz to 10MHz, in order to get sufficient current stabilization. Note that the model of Fig.6 is a very simple inductor model and that more sophisticated models have been developed and will be used in future designs [1].

The simple inductor model of Fig.6 is very useful to estimate the maximum power efficiency that can be achieved in the DC-DC converter due to the non-ideal behavior of the embedded inductor. Fig.7 gives the theoretical expression for this maximum power efficiency and identifies the main contributions.

$$\eta_{\max} = \frac{V_O \cdot I_O}{V_O \cdot I_O + R \cdot I_O^2 + \frac{1}{2} \cdot f \cdot C_1 \cdot V_{cc}^2}$$

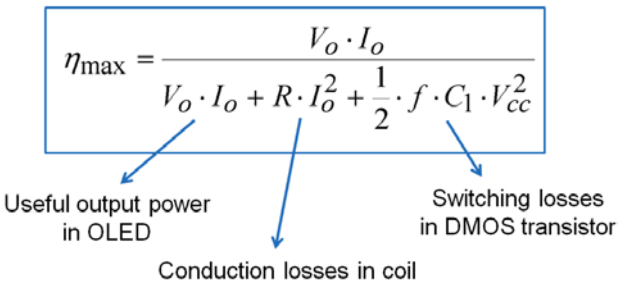

Fig.7: Maximum power efficiency that can be achieved due to the non-ideal behavior of the embedded inductor.

In this expression, V_o represents the DC output voltage across the OLED, I_o the corresponding OLED current, V_{cc} the supply voltage and f the switching frequency. It's interesting to put some numbers into this expression. Fig.8 shows the graph of the maximum achievable power efficiency as a function of the inductor parameters R and C_1, for fixed (typical) values of V_o = 7.4V, I_o = 340mA, V_{cc} = 40V and f = 10MHz.

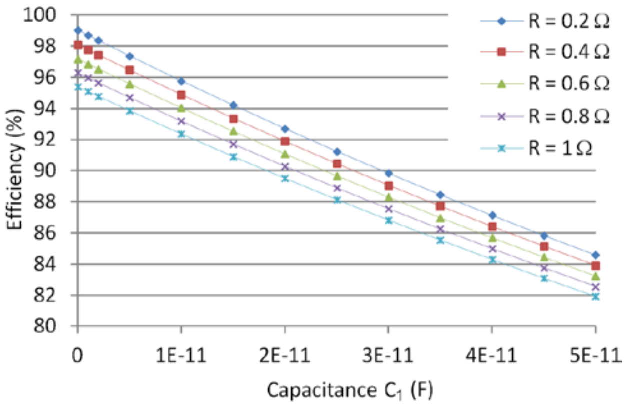

Fig.8: Impact of the embedded inductor parasitics on the power efficiency.

The negative impact of the inductor parasitics on power efficiency is quite clear. For the minimum R and C_1 values that are still considered realistic, 1Ω and 50pF respectively, the maximum achievable power efficiency becomes 82%. Taking into account that lots of other power losses were neglected in this formula (e.g. conduction losses in the main switching transistor and free-wheeling diode, power consumption in the buffers and level-shifter, effect of harmonics, etc.), a power efficiency of the order of 70% is probably much more realistic.

During the design of the OLED driver chip, several options regarding the specific implementation of the switching DC-DC buck converter were analyzed and compared: versions with n-type or p-type high-side switches, versions with diodes or actively driven n-type transistors as free-wheeling devices, converters employing the bootstrapping technique for driving the n-type high-side switch, etc. All these circuits were simulated in the I3T80 technology of ON Semiconductor, an 80V extension of a 0.35µm CMOS process, and in each case the transistor channel dimensions were optimized towards maximum power efficiency. The simulations revealed that the differences between the investigated versions in terms of power efficiency and silicon area are very small. It was therefore decided to select the version that constitutes the least complex design and offers the most reliable operation. The chosen converter block diagram is shown in Fig.9. The high-side switch is a p-type DMOS transistor, driven by a high-side buffer and controlled by a high-speed level-shifter. The buffer is powered by a floating 3.3V supply between the main 40V supply rail and the output of an on-chip 40V to 36.7V linear regulator. The free-wheeling device is an n-type DMOS transistor with shorted gate, source and bulk electrodes, acting as a PN junction diode between its drain and bulk.

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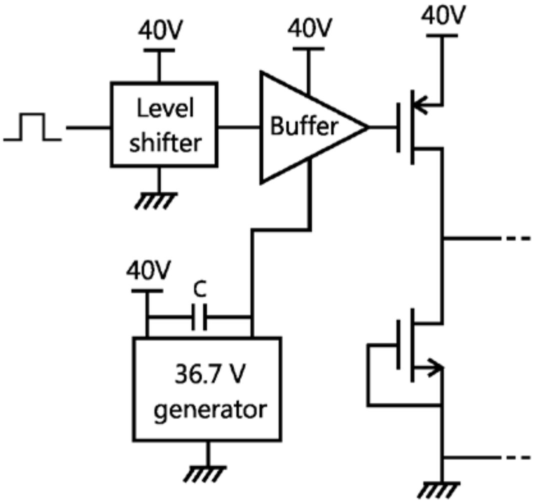

Fig.9: Selected DC-DC buck converter block diagram.

Simulations on the DC-DC buck converter circuit of Fig.9 revealed a global power efficiency of 71%, taking all losses in the chip and the embedded inductor into account, which is in perfect agreement with what was mentioned earlier.

Apart from the high-voltage DC-DC buck converter output stage for generating the OLED current, the chip also needs a sensitive feedback loop to adjust the OLED current and hence the OLED brightness to the desired value. Fig.10 gives the block diagram of this analog feedback loop.

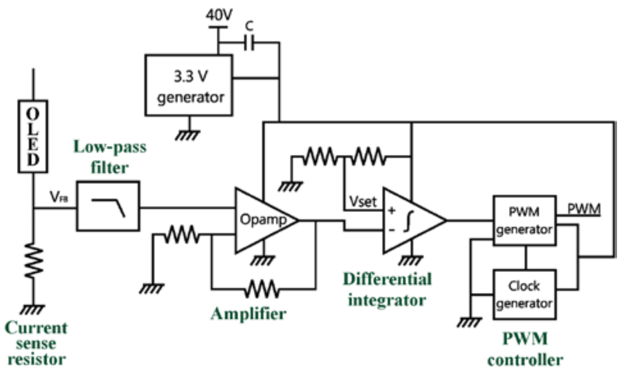

Fig.10: Block diagram of the analog feedback loop for controlling the OLED current.

The OLED current is measured by means of a small sense resistor connected in series to the OLED cell. This signal is filtered to get rid of noise and harmonics, is amplified and is then compared to the set value. The integrated error signal is finally used to adjust the duty cycle of the PWM control signal that is derived from an on-chip fixed-frequency clock generator. The whole analog feedback circuit is powered by an on-chip 40V to 3.3V linear regulator.

The layout of the whole OLED driver chip "Goldfish", designed in the I3T80 smart-power technology of ON Semiconductor, is shown in Fig.11. The total silicon area of the die is $4mm^2$.

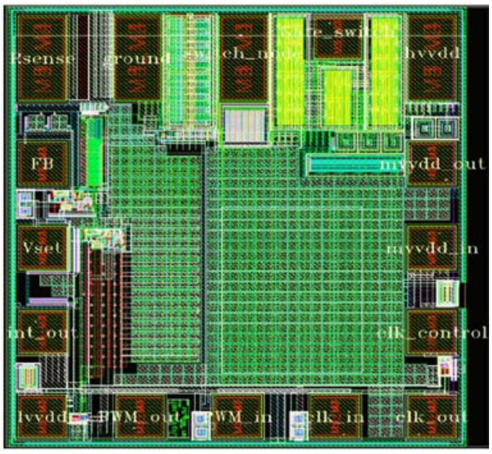

Fig.11: Layout of the OLED driver chip "Goldfish", designed in the I3T80 technology.

Note that this is a first prototype OLED driver IC, containing the basic functionality for driving and controlling the brightness of an OLED tile. Enhanced features, such as optical feedback for OLED ageing compensation or PLC communication techniques, will be implemented on future versions.

The "Goldfish" OLED driver chip is currently under evaluation and the first experimental results will be shown at the CSS 2013 conference.

4 Acknowledgement

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5 Conclusion

A high-voltage IC for driving and controlling an individual OLED tile in a modular large-area lighting system was presented. The chip comprises a PWM-driven DC-DC buck converter and a sensitive analog feedback loop for adjusting the OLED current and brightness. The chip was designed in an 80V 0.35µm-based smart-power technology.

References:

[1] J. Kundrata, A. Baric, "Design of a Planar Inductor for DC-DC Converter on Flexible Foil Applications", *Proc. of the 35th International Convention MIPRO2012*, pp. 54-59, May 2012.