Article

Integrated light sensing and communication for LED lighting

Massimo Ruo Roch [1,†,‡] **and Maurizio Martina** [2,‡]

[1] Politecnico di Torino; massimo.ruoroch@polito.it
[2] Politecnico di Torino; maurizio.martina@polito.it
* Correspondence: massimo.ruoroch@polito.it; Tel.: +39-011-0904147
† Current address: Politecnico di Torino
‡ These authors contributed equally to this work.

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Abstract: Solid state lighting is nowadays widely diffused both in residential and office or industrial environment. Ambient light sensing to modulate lamp power is typical, too, but sensors inside a lamp are a challenge, due to the high flux of these sources, which easily saturates nearby light detectors. Usually, separate sensing devices must be introduced in the system, thus increasing complexity and cost. In this work, a methodology will be presented, to allow integration of a light sensing device inside a lamp, using low cost circuitry to mitigate interactions between high power LED sources and sensing photodiodes. Moreover, the same circuit allows visual light communication among sources.

Keywords: LED, ALS, VLC, IoT, sensing

1. Introduction

Usage of white LEDs as light sources is rapidly pervading the market, with large scale marketing starting around 2010. However, the initial approach was to use these kind of devices just as a plug-in replacement for traditional lamps, i.e. incandescent and fluorescent sources. The driving force is mainly energy savings, around 50% with respect to fluorescent lamps, and up to 80% if compared to incandescent bulbs [1] [2].

Specific characteristics of LEDs, seen as electronic devices, opened new usage perspectives, as they are dramatically different from their predecessors. Main differences are as follows:

- Quasi linear dependence of light flux from current passing through the LED. This relationship allows to easily modulate the total emitted power just controlling the supplied current, leading to accurate light dimming in the environment. This can be used to save energy, or to improve user experience.
- Reduced dimensions. White LEDs have small dimensions (1mm $\times$ 1mm for a 1W source). Design of very small lamps is nowadays typical. The size reduction boundary is given by electronics size, and/or thermal considerations.
- High modulation speed. White LEDs can change their flux on the nanosecond timescale, allowing to use them both to illuminate, and to carry information, given a proper modulation scheme [3] [12].
- Complex driving electronics required. The light source, typically built from several parallel strings of series connected LEDs, is typically driven by a current generator, with output voltages in the range of 10V-100V, and output currents ranging from 100mA up to several Ampere. Moreover, regulations requires high power factor designs of the power supply unit if the lamp is

fed by AC line. Even in the case of DC fed lamps, power electronics is anyway needed, to have a fixed amount of light independent of temperature and input voltage.

Introducing light sensors in the environment to collect data about illumination, and to send them to a control unit able to change the flux emitted by LED lamps, is again a typical situation in the age of Internet of Things (IoT) [4].

The overall system is usually realized with physically separated objects. Specifically, the following devices must be introduced:

- Solid state lamps, with a control input to dim them.
- Light sensors, with a data output to send collected data.
- A central control unit, which, according to sensed information, modulates lamps power.
- A communication network, to join together these building blocks. Several solutions exist, both wired (e.g. DALI), and wireless (e.g. ZigBee)

Having separated sensors and lamps leads to a cost increase, as deployment costs are related to the number of different objects to be installed. On the other hand, integrating a light sensor inside a LED lamp is a challenge, as the high flux level of LED can easily saturate nearby photo sensors. Several topology have been suggested to overcome this problem [5] [6] [7], but anyway they still require to optically shield the sensor from the LEDs, and this is not practical in compact lamps.

Visual Light Communication (VLC) is rapidly gaining interest, too, both in indoor and outdoor environments [8] [9] [10], but main interest is in achieving high bandwidth efficiency, and LED lamps are mainly used as transmitters [11]. Besides, spread spectrum techniques are usually adopted [12].

In this work, instead, simplicity and cost is the driving force, to allow large scale deployment of ALS and VLC distributed systems fully integrated inside low cost LED lamps. In this context, high bandwidth is not a premium, as IoT system does not need to transmit too much information (ambient light levels, temperature, people presence, etc.)

2. Materials and methods

In a typical solid state lamp, represented in figure 1, a Power Supply Unit (PSU) convert the AC line voltage to a DC constant current. Usually this current is not perfectly constant, and it is slightly modulated at two times the AC line frequency, to satisfy High Power Factor (HPF) requirements. A single stage PFC is used, to minimize PSU cost. LEDs are then directly fed by the PSU. Last, the PSU, if dimmable, has a control input (DIM), used to change the amount of light emitted by the lamp. Several standards exists to control lamp power, like DALI, 0-10V analog control, or variable duty cycle PWM.

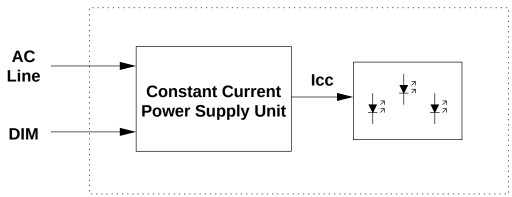


Figure 1. Standard LED lamp

The aim of this work is to design a block easily customizable to a variety of lamps, differents for power, size, and shape. From this point of view, it is mandatory to have a circuit with minimal complexity, but capable to operate in a broad range of operating conditions, too. In the proposed solution (figure 2), a control and sensing unit is interposed between the PSU and the LEDs. This block has the task to allow accurate Ambient Light Sensing (ALS), and, at the same time, to modulate emitted light in such a way to allow Visual Light Communication (VLC). The light sensor is a photodiode, which act both as a sensor for ambient light and as a receiver for optical signals coming from other lamps. The photodiode has an integrated optical filter, to resemble human eye responsivity.

This do not compromise receiver sensitivity, as typical white LEDs have good emission in the green region of visible spectrum, where photodiode filter has good responsivity, too.

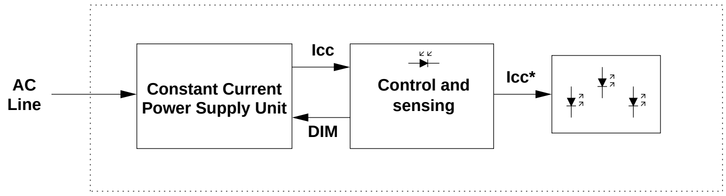


Figure 2. Modified LED lamp

To accomplish these functions, at each cycle of the AC line input the LEDs are turned off for a short interval (a negligible fraction of the cycle time). This interval is centered around the zero crossing of the sinusoidal input waveform. The usage of the AC line as a time reference gives best results, as it allows automatic synchronization of every lamp connected to the same power connection. Moreover, performing measurement and communication activities at a time in which the power line is crossing zero, minimizes errors due to interference's, both originated by the internal PSU, and injected from the outside.

Following LEDs turn off, a short amount of time must elapse, to accomplish photo detector and amplifier settling time. Now, a sequence of samples is gathered and stored, for further calculations. If no communication is needed, the average value of these samples represents the sensed ambient light level.

Figure 3. Modulation patterns

If communication is needed, instead, a modulation scheme must be introduced. The chosen approach is based on the emission of few pulses by the LEDs, injecting a controlled current. Zeros and ones are represented by different number of pulses at different frequencies. A key point is that the total energy must not change, to avoid visible luminance changes of the lamp as a function of the transmitted pattern. As an example, the two different modulations can be 4 pulses at 100kHz, and 8 pulses at 200kHz to represent '0' and '1', respectivly (figure 3).

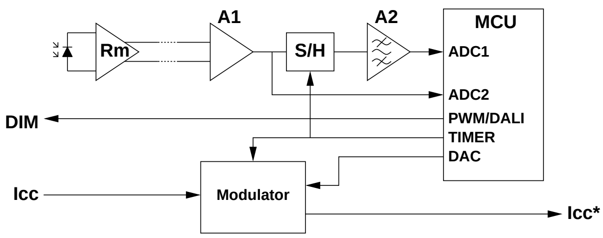


Figure 4. Control and sensing block

The internal structure of the circuit designed to implement the above functionalities is depicted in figure 4.

A photodiode, with spectral response resembling the human eye one, feeds a transresistance amplifier. It has a differential output, as it must be mounted on the front of the lamp, near the LEDs, and the noise level along the cables can be quite high. The lamp PSU itself has nodes swinging from 0 to 700V at 20kHz-200kHz, generating significant EMI. Besides, the gain of the transresistence amplifier is limited, as it must not saturate even when the LEDs are turned on. It means the signal measured when LEDs are turned off has limited amplitude, and a single ended approach would degrade precision and reliability.

The differential signal is fed to an instrumentation amplifier (A1), used to eliminate common mode noise, and then sent to a sample-and-hold. This one is in hold mode when LEDs are turned on, and in sample mode when they are turned off. Its task is to minimize transients at the input of the successive stages, allowing an easier design (and higher gain) of the following band-pass filter A2. In fact, an abrupt change at the input of the filter (fall down of the LED power - see figure 3) would be anyway amplified, and must be avoided. A2 is introduced to further improve SNR, and to increase sensitivity.

The output of A1 and A2 are sent to a microcontroller (MCU), which samples the signals while LEDs are off, and store them for further computations. Signal processing algorithms are executed while LEDs are on, in the remaining portion of the AC line cycle.

Two different calculations must be performed:

- ALS. The actual value of measured luminance is obtained simply averaging the samples acquired while LEDs are off, but outside the communication interval.
- VLC. To detect the received bit, a differential approach is used, comparing the amplitude of the frequencies corresponding to ’0’ and ’1’ respectively. To obtain a boost in sensitivity, the samples are pre-processed through two Goertzel filters, centered on the desired frequencies. These filters [13] [14] are marginally stable, but they can be efficiently used with short sequences.

Light modulation is implemented by the modulator block of figure 4. A simplified schematic is visible in figure 5. It is basically a switch, used to interrupt the current flow from the lamp PSU, and a current generator, driven by the DAC output of the MCU. The current generator is implemented through a current mirror with gain. The gain is needed as LEDs driving current is typically two order of magnitude greater then the output current capabilities of the DAC. The switch is implemented through a pair of source coupled NMOS transistors. This topology cancels the presence of the body diodes, allowing to block current flow in both directions when switch mosfets are both turned off. (right side of the figure).

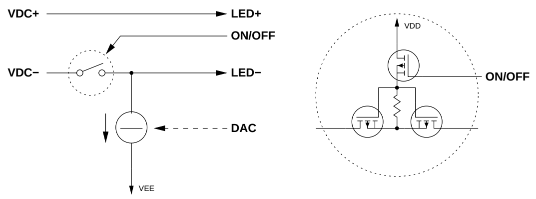


Figure 5. Details of the modulator block

3. Results

A physical implementation has been designed, using off-the-shelf discrete components, and simulated, taking in account parasitics. The circuit has been designed in the hypothesis to insert it inside a T8 form factor LED tube. Special care has been taken to reduce overall cost, obtaining a module which requires less than 10 US$.

In figure 6 relevant waveforms of the ALS and VLC blocks are shown. The upper waveform is the signal at the input of the S/H, and the center one is the output of the S/H, showing almost complete cancellation of LEDs turn-on/turn-off transients. Last, bottom waveform is the modulated signal at the output of the band-pass filter, sent to the input of the A/D converter into the MCU, to be processed by the two Goertzel digital filters.

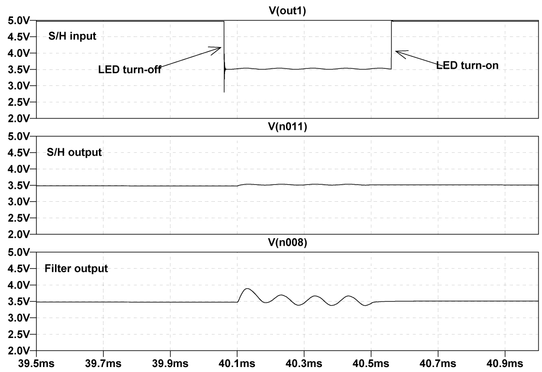


Figure 6. Simulation output

The board has been then built, and it's final layout is depicted in figure 7. Coloured rectangles identify the main building blocks of the realized architecture. From left to right, they are:

1. Blue frame: power supply of the board. To accomplish the usage inside a variety of different lamps, a simple linear regulator has been designed, to generate 5V and 3.3V from the unregulated DC input supply rail. Moreover, a flyback is introduced, to generate the VEE rail (currently at -12V), used to feed the modulator circuit. The latter is directly driven by a PWM generated from the microcontroller. This way, it can be turned off as needed, for example to minimize noise during receiver sampling phase.
2. Green frame: microcontroller unit. A 48 MHz low power ARM is used, to have enough computing power for data processing (digital filters). The implemented program include both VLC, and automatic dimming based on ALS. Actual code footprint is 16kB of code and 2kB of data, leaving space for introduction of further functionalities in the future.
3. Yellow frame: power switch and modulator. The switch is built up of low R_{DSon} power mosfets, maximizing power efficiency. The modulator is a current mirror, with BJTs as active lements. They are used for the good precision achievable at low cost in a discrete design.
4. Red frame: signal conditioning and sampling. A quadruple operational amplifier is used to implement the circuitry described in the preceding sections. A discrete low resistence, low leakage current switch is used to build up the S/H function.

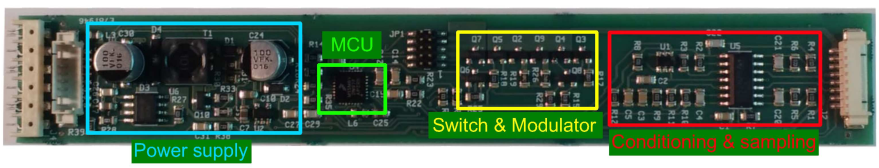
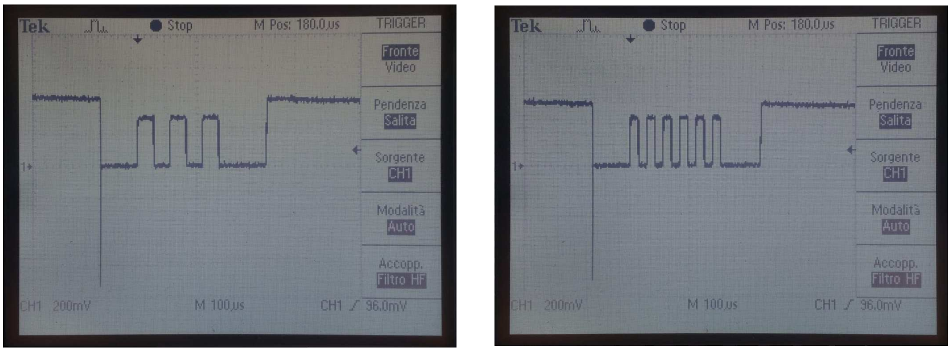


Figure 7. T8 tube control and sensing board

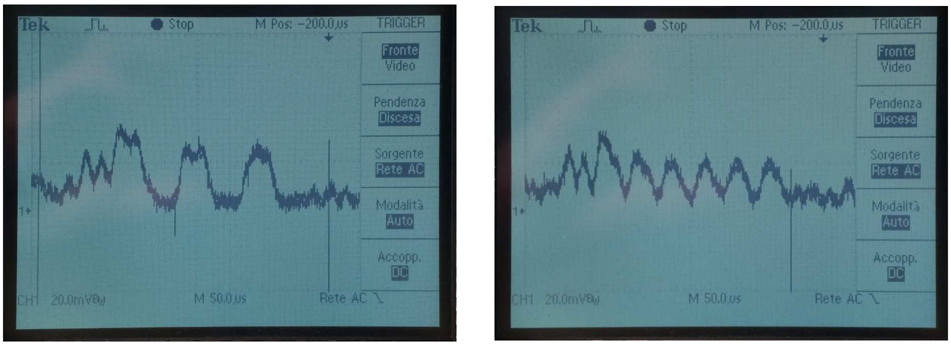
Measurements have been performed in a real environment, inserting the control board in a LED T8 tube, fed by 230V AC line. In the following figure 8, the currents fed to the LED string in the case of '0' and '1' transmission are shown, as required by the transmission protocol described above. Three pulses are used for '0', and 6 for '1'. The action of the power switch which turns off and on the LED light is visible, too, just before and after modulation pulses. ALS sampling is performed when LED is off, of course. The slight misalignment in LED current in the left and right sides of the image is correct, as light current is modulated at 100 Hz by the PFC to achieve near-unity power factor (0.99 at 10W in this case).



(a) ’0’ **(b)** ’1’

Figure 8. LED current: bit transmission

The measurements in the receiving side are instead visible in figure 9. Due to the strong signal attenuation related to distance between the transmitting and the receiving lamps, only the processsed signals just at the input of the microcontroller can be shown, after preamplification, noise cancelling, sampling and filtering. These signals will be then digitally processed by the microcontroller. On the left, the signal corresponding to a ’0’ is shown (3 pulses), while at the opposite side a ’1’ is received (6 pulses at doubled frequency). As it can be easily seen, the signal is clearly emerging from the noise, even if at reduced voltage levels ($20mV_{pk-to-pk}$). This is a considerable result, given that at about 5cm, and without any kind of shield, there are nodes switching at $600V_{pk-to-pk}$, 100kHz.



(a) ’0’ **(b)** ’1’

Figure 9. Microcontroller ADC input

Conflicts of Interest: “The authors declare no conflict of interest.”.

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