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An optical sensing approach based on light emitting diodes

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Abstract. An extremely simple optical-sensing technique has been developed for various applications. The proposed sensing system employs one, two or more LEDs whereby each one can be used as a light emitter or light detector. The main advantages of the proposed pulse based signal conversion technique are that it leads to better spectral sensitivity; increased and adjustable resolution; reduction in cost, dimensions, power consumption and it avoids the need for expensive and precise operation amplifiers, ADCs and other external components. The sensing configuration presented here, uses only two I/O pins of standard microcontroller, one or two LEDs and is capable of detecting various optical effects. Using multi-configurable I/O pins the LED used as a light detector is reverse biased so that the photocurrent generated by the incident light discharges its inherent capacitance throughout Hi-Z input impedance. A simple timer circuit that measures the decay-time taken for the discharge process from logic 1 to logic 0 provides direct digital output proportional to the light intensity. This sensing concept has been tested in many applications and some of them are described here.

1. Introduction

Light emitting diodes (LEDs) are robust, low-cost, low-power, energy efficient, small size optical components, widely used in consumer electronics, and in more specialist applications as the illumination sources for fibre optical sensors and reflectometers. As light emitters they cover an increasingly broad spectral range from UV to near infrared. However, it has been little forgotten that the LED has also the ability to detect light quite well and that it can be used as an inexpensive, readily available, optical detector for the range of applications. Usually it is able to detect the light at the wavelengths shorter than it emits and as such it can act as a good wavelength selective detector. For example, a LED that emits greenish-yellow light at the peak wavelength of about 555 nanometers (nm) detects green light at the peak wavelength of about 525 nm and over the spectral width of 50 nm. Almost every LED is capable to detect a relatively narrow band of wavelengths, with different sensitivity. Moreover, a standard LED can even perform double-duty in the same circuit without changing its physical or electrical connections.

A LED used as a photodetector can operate in two detection modes: *photovoltaic* mode, where the device is capable of producing a voltage when exposed to light; and *photoconductive* mode, where the device's electrical conductivity is controlled by the exposure to light. The first concept was used by [1] for implementation matrix of tactile sensors. The photoconductive mode was explored by [2], where LEDs were used to detect sunlight intensity. Using similar approach, the researchers in [3] evaluated the potentional of LEDs as high-speed, wavelength selective photodetectors. In both detection modes the produced signals, photo voltage or photocurrent (which is usually around 10–100 times smaller than standard photodiode's equivalent) could not be registered without strong amplification. Thus, expensive precision OPAMPs and picoammeters connected to the external ADC chip, or to the expensive microcontroller with high-resolution inbuilt ADCs, are usually used to digitalize such signals.

Our work shows that very accurate and precise measurement of the LED photocurrent is possible without the need for amplification and for internal or external ADCs. Instead of them, the photo current is measured using inherent capacitance of diode itself (typically picoFarads), bi-directional microcontroller I/O ports with configurable internal pull-ups or tri-state Hi-Z states and built-in digital timer-counter. This extremely simple and low-cost approach provides digital measurement of light intensity, while simultaneously providing excellent signal-to-noise characteristics, due to the signal integration over the measurement. In addition, these configurations require extremely low supplying power since controller itself provides supply for sensing probe, usually operating in impulse (chopper) mode. As such, the principle is especially suitable for low-power, miniature, portable instruments as well as in light switches, photo-keyboards, high-resolution dimmer, code detectors, smoke detectors, proximity detectors, colour detectors [4], chemical instruments and so on. Also, the proposed principle could be efficiently employed in optical non-invasive medical measurements [5] (like pulse oximetry, heart rate, blood pressure, etc.).

In the following sections, the proposed approach with basic sensing configurations is illustrated. After that experimental results are presented through various applications, followed by the discussion, conclusion and basic references.

2. Sensing approach and circuits

2.1 *Single-LED configuration.* The proposed sensing approach is presented through the description of the simplest sensor configuration – single-LED photo relay. It consists of a single LED connected to two microcontroller's pins, Figure 1. The very same LED also measures the intensity of incoming light and indicates if it is over or under pre-defined threshold.

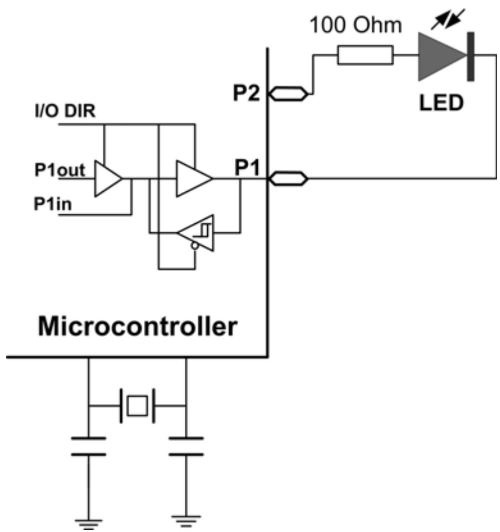

Figure 1. Microcontroller and standard LED as light emitter-detector.

In the detector mode the LED is charged up to +5V very quickly (100-200μs), "STEP 1", Figure 2(a). The charge is the sustained by the inherent capacitance of the diode (typically 10-15 pF). Thence, the pin P1 is switched into the Hi-Z input mode (approximately 10^{15} ohm resistance), "STEP 2". Under the reverse bias conditions, a simple equivalent-model for the LED is a capacitor in parallel connection with a current source $i_R(\Phi)$, which models the photocurrent, induced by the incident light intensity Φ, Figure 2(b). The leakage current i_L through the pin P1 (usually 0.002 pA) is insignificant compared to a typical photocurrent $i_R(\Phi)$ of 50 pA through the diode itself, under the normal ambient lighting. Analytically considered, the discharging process of Cr can be expressed as:

$$v_{P1}(t) = V_{CC} - \frac{1}{C_r}\int_o^t i_R(\Phi, t)dt \quad (1)$$

Assuming that $i_R(\Phi)$ has constant value, the above Equation can be rewritten as:

$$v_{P1}(t) = V_{CC} - \frac{1}{C_r} i_R(\Phi)dt \quad (2)$$

which shows that $v_{P1}(t)$ linearly decreases by time t to zero. Using a software timing routine, based on 16bits microcontroller timer/counter (TCNT1), we continually poll the voltage $v_{P1}(t)$ through its digital equivalent, logic state of the input pin P1in, until the logic "0" threshold V_{TR} (~ 2.2V) is reached. The decay time *Td*, normally measured in microseconds, is inversely proportional to the amount of the light detected and hence we can calculate the diode photocurrent $i_R(\Phi)$. Analytically the Td could be expressed as:

$$T_d = \frac{C_r}{i_R(\Phi)}(V_{CC} - V_{TR}) = N_{TCNT}T_{clk} = N_{TCNT}\frac{1}{f_{tclk}} = N_{TCNT}\frac{1}{N_p f_{clk}} \quad (3)$$

where N_{TCNT} represents the integer number of timer's counts, f_{tclk} the timer's clock, *Np* the pre-scale factor (1/2, 1/8, 1/64, 1/256, 1/1024) and f_{clk} the main clock frequency. *Td* decreases when the amount of light received increases, and the diode discharges more rapidly, and therefore, when the amount of light received decreases the diode discharges more slowly and *Td* increases. By measuring the *Td* with the emitter LED on and off, the differential can be ascertained and compensation made for the effects of ambient lighting. The measurement of *Td* depends on f_{tclk} and could be adjusted by the general micro-controller clock depending on the choice of *Np*.

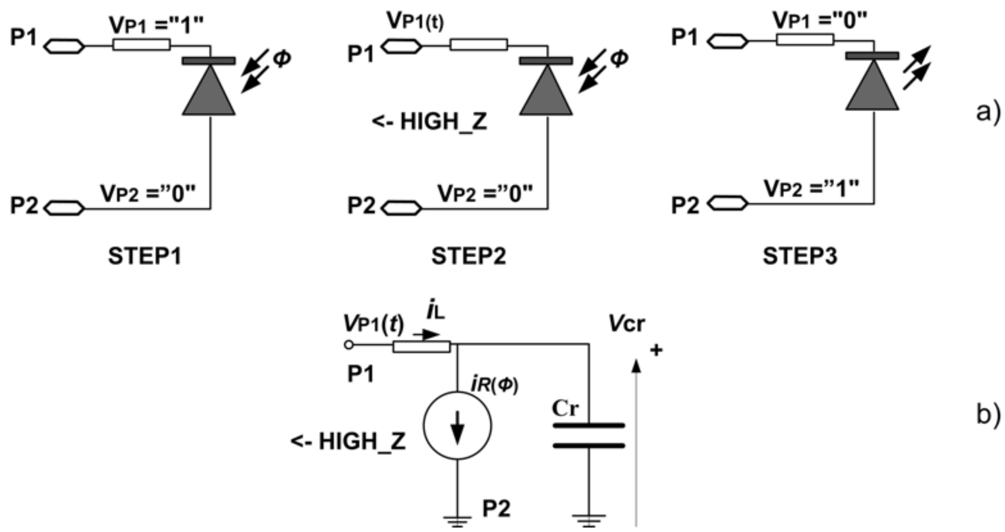

Figure 2. a) Double-duty of LED in process of light detection/emission. b) Equivalent circuit during LED discharging process.

If the decay time is longer or shorter than specified threshold value *Tdcr* (called critical), the LED is switched on to emit light. For example to alarm us by blinking, "STEP3", Figure 2(a). Additionally,

the other pins of the microcontroller can be used as relay output or light controlled pulse-width-modulation outputs.
2.2. *Two-LEDs configuration.* This configuration also occupies two I/O pins, Figure 3. It is used as a simple LED-LED distance meter, proximity detector, colourimetric analyser, non-contact key-pad, smoke detector, heart rate (HR) detector, etc. There are two distinctive modes of photo detection using this sensor, a transmission mode and a reflection mode. While in the transmission mode emitter is on one side of the test sample (target) and the detector on the other, Fig. 3.; in the reflection mode the emitter and detector are placed in parallel, allowing measurement of backscattered light. Different LED combinations could be used as emitter-detector (IR-IR, IR-RED, RED-RED, RED-WHITE, etc..)

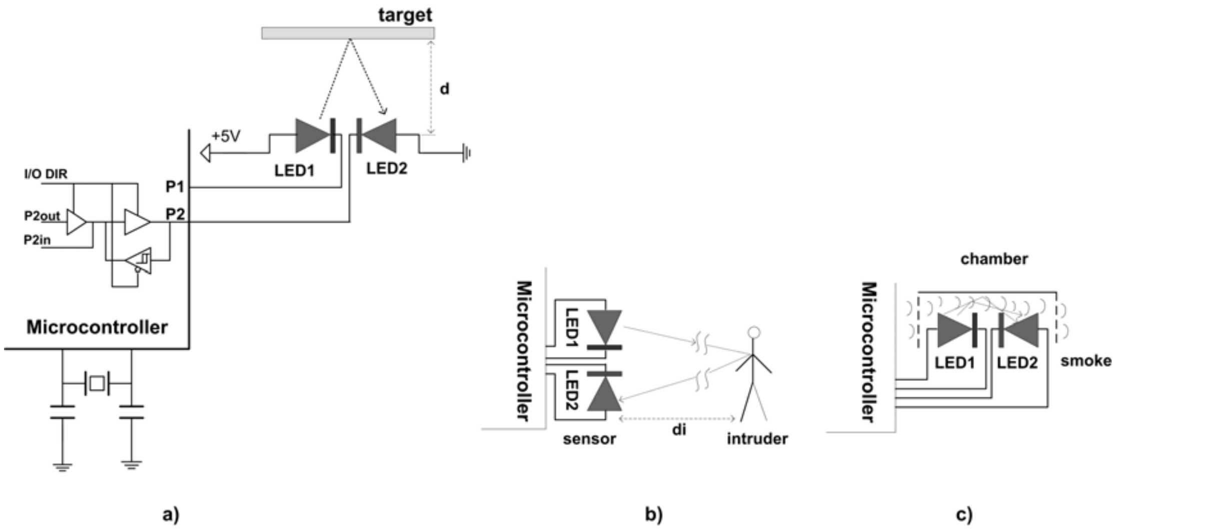

Figure 3. Two LEDs sensing combination as distance meter (proximity detector) (a) and access-presence detector (b) and smoke detector (c)

3. Experimental results

In order to verify proposed sensing method a several typical experiments have been performed using different sensing combinations. An 8bits AVR RISC ATtiny90S2313 micro-controller (ATMEL corporation) running at 8MHz, allowing the resolution of 0.125µs (8MHz), was used to implement sensing protocol and to measure the decay time (*Td*).

3.1. *Testing results of the single-LED configuration.* The capacitance of light emitting diodes is typically of the order of picoFarads. Hence, the discharge time for such devices will be small ranging from microseconds under bright light to milliseconds in low light conditions. The experimentally recorded traces from Figure 4(top) illustrate the process of LED discharging, $v_{P1}(t)$, for two levels of Φ, Φ_1 and Φ_2, thus $\Phi_2>\Phi_1$. Figure 4(bottom) shows the voltage output of pin P2 during operation steps and trice when the same LED is turned on, indicating Td<Tdcr (Tdcr=Decay time critical). High-Bright 5mm (670nm) RED LED is used for light detecting and emitting.

3.2 Testing results of two-LEDs configuration. Here we tested proposed combination for various applications: (i) distance meter and proximity detector, Figure 3(a), (ii) access-presence detector by photo barrier, Figure 3(b) and (iii) smoke detector, Figure 3(c). The sensing probe comprised an IR(910nm)-IR(910nm) 5mm LED combination in reflectance mode. Figure 5 presents some of preliminary results obtained during testing. The same microcontroller and clock were employed.

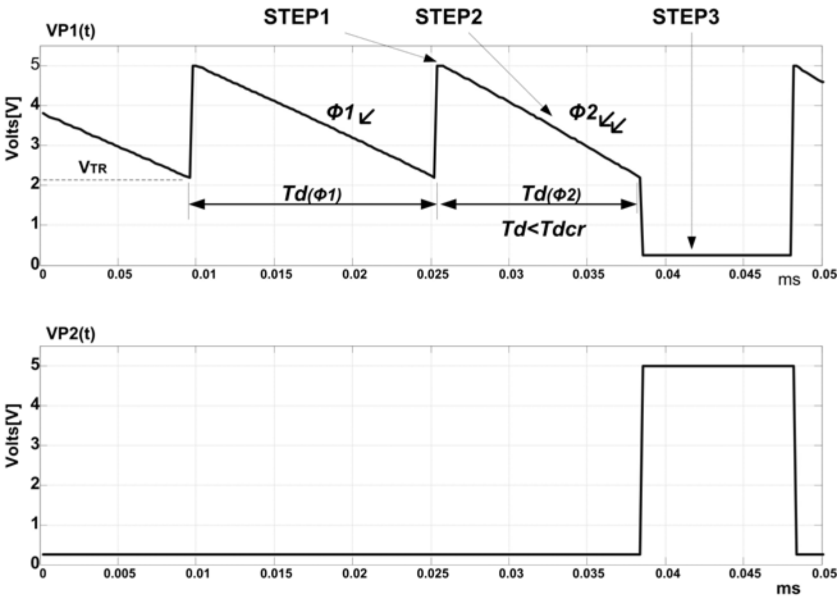

Figure 4. (top) pin P1, experimentally trace of LED charging/discharging process, (down) pin P2 trace.

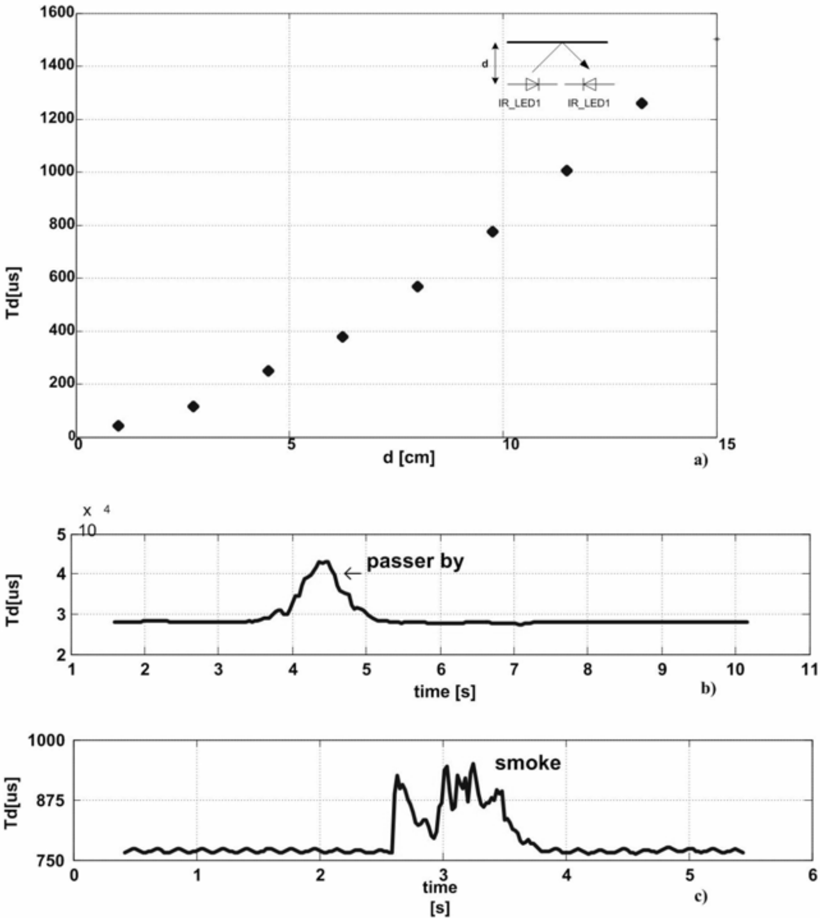

Figure 5. (a) IR-IR distance meter, IR-IR access-presence detector, IR-IR smoke detector.

3.2 Temperature dependence. Temperature variations have multiple and very complex effects on the proposed sensor configurations. In the case of the receiver diode, parameters such as reverse current, capacitance and dominant wavelengths are temperature dependent and for the transmitter diode, the luminous flux and dominant wavelengths are related to temperature. Also, the micro-controllers I/O pin input threshold for constant supply drifts slightly with temperature.

In the case of single-led combination the percentage change of *Td* in relation to temperature is k1=-1.35%/°C. It means that the *Td* decreases with increased *temperature* because the reverse photo-current of the receiver LED increases as the temperature does. The normalization has been done to 25°C. For two-LEDs combination the *Td* for a temperature range of 0˚C to 50˚C, using the IR (910nm) – IR (910nm) LED configuration. These limits were chosen because they best represent the typical ambient temperature range for the ambient temperature of an operating sensor device. The approximation shows that *Td* increases by ~20% over the 50˚C temperature range, or 4% per 10˚C (k_2=0.4%/˚C). It means that temperature effect of emitter diode is dominant (the luminous flux of the emitter LED decreasing)

4. Conclusion

In this paper we have demonstrated an example how standard LEDs can be used as both light emitter and light detector. A single, pair or more of LEDs connected to I/O pins of standard microcontroller are used as sensitive sensors for various optical applications. The proposed sensing protocol is fully software implemented and removes the necessity for the precise operational amplifiers, high resolution ADCs and other external components. The power consumption of such sensor is very low making it suitable for portable battery-powered instruments. Some of the targeted applications are briefly described and illustrated with some real experimental results.

References

[1] Rossiter J and Mukai T 2005 A Novel Tactile Sensor Using a Matrix of LEDs Operating in Both Photoemitter and Photodetector Modes *Proc of 4th IEEE International Conference on Sensors (IEEE Sensors 2005)* (IEEE-Press) p994.

[2] Brooks R and Mims M 2001 Development of an inexpensive handheld LED-based Sun photometer for the GLOBE program *Journal of geophysical research* **106**, 4733–4740.

[3] Miyazaki E, Itami S and Araki T 1998 Using a light-emitting diode as a high-speed, wavelength selective *Review of scientific instruments* **69 11** 547-588.

[4] Lau K T, Baldwin S, Shepherd R L, Dietz P H, Yerazunis W S and Diamond D 2004 Novel Fused-LEDs Devices as Optical Sensors for Colorimetric Analysis *Talanta* **63 1** 167-173.

[5] Rhee S, Yang B H and Asada H H 2001 Artifact-Resistant Power-Efficient Design of Finger Ring Plethysmographic Sensors *IEEE Transactions on Biomedical Engineering* **48 7** 795-805.