Practical implementation of integrated ambient light sensors in visible light illuminance measurements

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Modern Ambient Light Sensor (ALS) integrated circuits can be used not only in control and automation tasks they have been designed for but due to their useful additional features can also be implemented at the heart of measurement platforms to characterize illuminance levels as perceived by the human eye too. The article describes a practical implementation of such a device in photopic measurements and gives a detailed insight into the OPT3001 sensor structure and function, the communication protocol used to transfer digital data to a system microcontroller and the processing and display system hardware itself. A block diagram description of the device specific firmware follows with different subroutines listed to address not only the specific hardware configuration and error processing tasks but the measurement reading, processing, conversion and display tasks as well. The device concept functionality has been verified by some measurements performed on a standard high power LED device parameters (luminance flux) showing good coincidence with manufacturer data and even the potential for obtaining more illuminance related data as available with such a simple highly integrated and cost-effective measurement platform.

Практическо приложение на интегрални сензори на осветеност за фотометрични измервания (Емил Владков). *Модерните интегрални сензори на осветеност намират приложение не само при реализация на задачи по управление и автоматизация, но благодарение на полезните си допълнителни характеристики могат да бъдат ядрото на измервателни платформи за фотометрични величини. Статията описва практическа реализация на устройство на база интегрален сензор OPT3001, като запознава детайлно със структурата и функционалността му, използвания комуникационен протокол, както и с хардуерната система за обработка и представяне на резултатите. Включено е и описание на специфичното програмно осигуряване, включващо подпрограми за конфигуриране на сензора, обработка на грешки, прочитане, конверсия и представяне на резултатите. Функционалността на концепцията се потвърждава от измервания на параметрите на стандартен мощен светодиод, показващи добро съвпадение с каталожните данни, както и потенциала за получаване на по-подробни резултати с относително проста, високоинтегрирана и икономически ефективна измервателна платформа.*

I. Introduction

The illumination of working places and human living ambient can strongly influence the physiological processes in the human body and even the psyche. Insufficient illumination directly threatens human vision but also can have several adverse side effects on human work activity, for example fatigue, reduced productivity and even accidents. A rise in illumination levels from 100 to 1000 lx can increase productivity from 5% to 40%, depending on the nature of the activity [1]. Usually standards determine illumination measurements to be done – for example horizontal illuminance measurements (at the working place), vertical illuminance measurements (blackboards and whiteboards, shelves) and cylindrical illuminance measurements, representing vertical measurements done 90º apart and averaged [2,3]. The indicative norms for illumination of study rooms and office places suggest average illuminance levels of at least 500 lx. Emergency evacuation lighting on the other hand, which is obligatory for the operation of buildings with more than 50 inhabitants, shall guarantee at least 0.5 lx floor illuminance level. Related to the illumination topic is the illumination non-uniformity rate, which represents the lowest to the mean illumination ratio at the working place.

Illuminance level measurements can not only characterize the working environment quality, but also they can be used in automation systems for light sources intensity control and for indication and signaling system visibility adaptation, for example in street and traffic lights.

Usually the conformity with the good illuminated working environment sanitary norms and standards is verified through continuous measurements with instruments called **lux-meters**. These devices consist of a photosensitive element, amplification circuit, converter and a result interpreting and representing system, which can be both analogue and digital.

The light intensity measurement task is greatly simplified nowadays because of the vast majority of integrated ambient light sensors (ALS) offered by many semiconductor companies. These ALS devices integrate the photosensitive element and the additional electronics to perform the analogue-to-digital conversion and incorporate many additional features too, as illuminance threshold values triggering events reporting when exceeded, consecutive measurement results averaging, automatic range setting function, interrupt generation for the managing microcontroller to read the results and several others.

II. Photopic illuminance measurements

In photometry the measurements of light are referenced to the brightness perceived by the human eye in contrast to radiometry, which makes measurements referenced to the absolute power of light as radiant energy [4]. In photometry the radiant power is weighted at each wavelength by the so called luminosity function, which models the human eye sensitivity. The luminosity function adapted to day-time is called the photopic sensitivity function (represented in Fig. 1 [4]), and if it is darkness-adapted is called the scotopic sensitivity function.

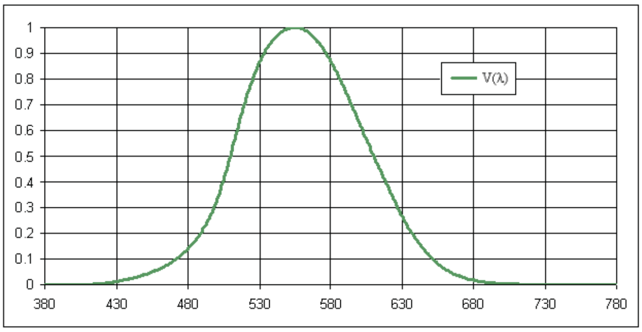

Fig.1. Spectral luminous efficiency of photopic vision – photopic sensitivity function.

If an ambient light sensor has to be useful in visible light intensity measurements related to the human lighting experiences, then the sensor's spectral response shall tightly match the photopic response of the human eye, which includes significant infrared rejection too.

The single chip lux-meter OPT3001 evaluated by this work measures the intensity of light as visible by the human eye regardless of the light source with precision human-matched spectral response and strong IR rejection as it is designed for systems that create light-based experiences for humans [5]. The spectral response of OPT3001 compared to that of the human eye is shown in Fig. 2.

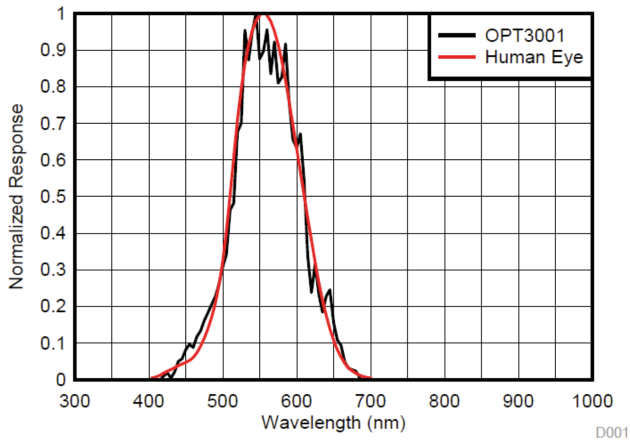

Fig.2. Spectral response of the OPT3001 and the human eye compared.

III. Ambient Light Sensors types

A classification of the different light sensing technologies available for measurement purposes too is presented in Fig. 3 [6]. The Cadmium Sulfide (CdS) photoelectric cells match the human eye response, but contain a prohibited material (Cd), which makes their application at the consumer market a little bit difficult. Photodiodes have a relatively low dispersion between individual units, but their low output current makes the use of an external amplification circuit mandatory. Phototransistors have good output drive capabilities, but poor temperature behavior and large dispersion between units, which demands additional calibration steps. The Ambient Light Sensor (ALS) technology addresses all these shortcomings and can be additionally subdivided in Analog ALS integrated circuits (IC's) and Digital ALS IC's. The typical Analog ALS IC combines a photodiode, a current amplifier and a general control circuitry with the output being analog current converted to voltage by means of a simple resistor. To be interfaced to a system microcontroller an additional conversion process by an ADC is needed for this technology. On the other hand the Digital ALS IC integrates the ADC converter and can be easily interfaced to the system microcontroller through the I^2C bus, as is the case with the evaluated OPT3001 sensor.

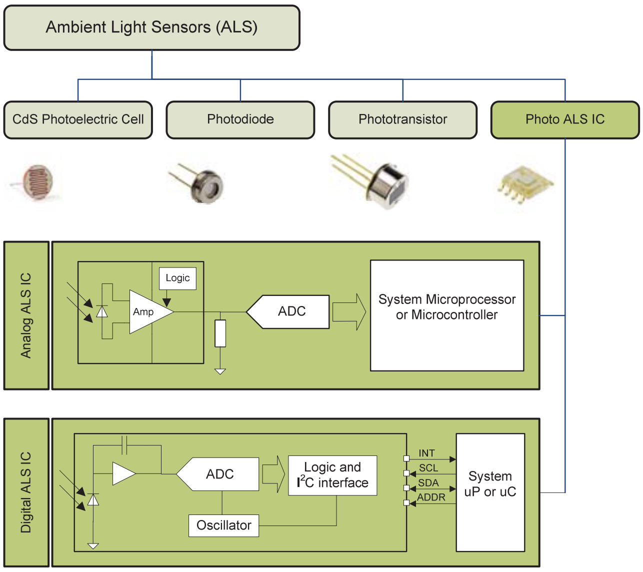

Fig.3. Classification of ALS technologies.

IV. The OPT3001 Ambient Light Sensor description and features

The functional block diagram of the Texas Instruments OPT3001 device matches the description of the Digital ALS IC given in Fig. 3 and is presented in more detail in Fig. 4 [5]. The circuit is fully self-contained and can measure illuminance levels ranging from 0.01 lx to 83865.60 lx. After conversion it communicates the result digitally over the I^2C bus. The result can trigger an interrupt (via the INT pin) to a processor, or can be compared to a window with Low and High limits of illuminance levels (register programmable) and again can alert a system or trigger and interrupt.

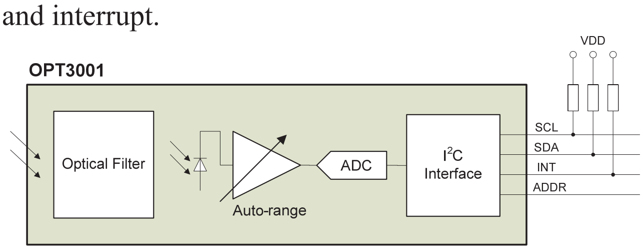

Fig.4. OPT3001 functional block diagram.

The automatic full-scale range-setting mode selects the optimal range for every lighting condition releasing the burden of iterative cycles of measurements and readjustments from the user software. The auto-range mode is accomplished with the help of a 10 ms range assessment measurement to determine the appropriate full-scale to make the regular first measurement after entering this mode and then using the results of the previous measurements for the subsequent measurements. Depending on the result being towards the lower or upper side of the full-scale, the range is decreased or increased. If the full-scale range is exceeded due to a fast optical transient event the current measurement is aborted without being reported and a new 10 ms assessment measurement is taken.

Continuous or single shot measurement modes are programmable with integrating times for the result to be complete of either 100 ms or 800 ms. As the device starts in low-power state, it has to be properly initialized by the system firmware. The optical filtering system of the device is not excessively sensitive to dust particles or micro shadows on the optical surface of the IC, nevertheless keeping the optical surface clean is recommended for best results.

Communication over the serial I^2C bus is standard with the master issuing the start condition over the bus and then addressing the OPT3001 device via the slave address byte consisting of seven address bits and a direction bit to distinguish between read and write operation. Four I^2C addresses are possible by connecting the ADDR pin of the IC to one of the other pins: GND, VDD, SDA and SCL, as shown in Table 1. Every transaction on the serial interface is terminated by the master with a stop condition.

Table 1

Possible OPT3001 I^2C addresses and their configuration

OPT3001 I^2C address	ADDR pin connection
1000100	GND
1000101	VDD
1000110	SDA
1000111	SCL

Configuration and result reading occurs on the OPT3001 through a set of dedicated registers with their distinctive addresses as shown in Table 2. To initialize and change the mode of operation some of the registers are written by the host microcontroller. The Write operation consists of the following sequence of events: the master addresses the slave with its slave address with the last R/W\-bit set to low (write); the next byte is the address of the register the data has to be written to; the next two bytes represent the data written to the addressed register; every byte transmitted on the serial interface is acknowledged by the OPT3001; the master terminates the transfer with a stop condition. To obtain the result data the result register has to be read by the host microcontroller.

During the read operation the following sequence of events happens: the master writes in a separate write operation (embedded in a start-stop condition of the bus) the register address of the register, which has to be read; the master issues a start condition, followed by the slave address byte with the last bit set high (read); the OPT3001 transmits two bytes (MSB first) with the data to be read by the master – in the evaluated design case the measurement result; the read data has to be acknowledged by the master; the master issues a stop condition. The timing diagrams for the I²C transactions as they occur in the design presented are given in Fig. 5. The host microcontroller writes to the Configuration and the Low Limit registers and reads the result from the Result register and the proper timing for these operations to occur is achieved through the firmware routines.

Table 2

OPT3001 register map

Register name	Register address
Result	00h
Configuration	01h
Low Limit	02h
High Limit	03h
Manufacturer ID	7Eh
Device ID	7Fh

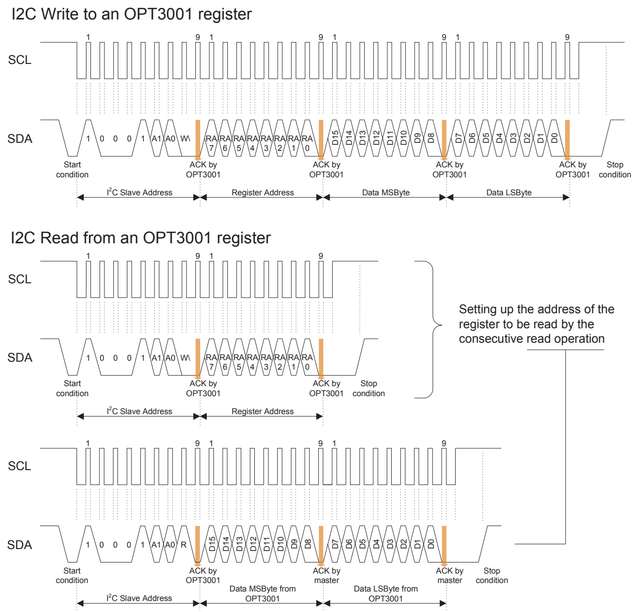

Fig.5. OPT3001 register write and read timing diagrams.

The interpretation of the individual bits of the OPT3001 registers accessed in software during ititialization and continuous result reading is given in the register maps presented in Fig. 6. The exponent field of the result register represents the resolution or the LSB size in lx of the result R[11:0] field. The actual expression used by the firmware to translate the result register content into an lx-value is given with equation (1) with the interpretation of the exponent as a resolution in lx shown in (2).

$$LX\_result = LSB\_size \times R[11:0], \quad (1)$$

$$LSB\_size = 0.01 \times 2^{E[3:0]}. \quad (2)$$

Result Register (address = 00h)

Bit number	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Bit meaning	**E3**	**E2**	**E1**	**E0**	**R11**	**R10**	**R9**	**R8**	**R7**	**R6**	**R5**	**R4**	**R3**	**R2**	**R1**	**R0**
Access type	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R

Configuration Register (address = 01h)

Bit number	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Bit meaning	**RN3**	**RN2**	**RN1**	**RN0**	**CT**	**M1**	**M0**	**OVF**	**CRF**	**FH**	**FL**	**L**	**POL**	**ME**	**FC1**	**FC0**
Access type	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R	R	R	R	R/W	R/W	R/W	R/W	R/W

Register fields explanation and their values as loaded by the firmware:

RN[3:0]: Range field – selects the full-scale range of the ALS IC; loaded with **1100b** for automatic full-scale setting mode.

CT: Conversion time field – determines the length of the digital conversion process with 100 ms and 800 ms choices; loaded with **1b** for 800 ms conversion time.

M[1:0]: Mode of conversion operation field – selects between shutdown, single-shot or continuous conversion modes; loaded with **11b** for continuous operation.

OVF: Overflow flag field – indicates device overflow condition due to exceeding device illumination leves, indicated by full-scale or absolutely; read-only, left to **0b** as the reset value.

CRF: Conversion ready field – indicates when a conversion is complete; read-only, left to **0b** as the reset value.

FH: Flag high field – indicates that the result is larger than the level in the High-Limit Register; read-only, left to **0b** as the reset value.

FL: Flag low field – indicates that the result is smaller than the level in the Low-Limit Register; read-only, left to **0b** as the reset value.

L: Latch field – controls the functionality of the interrupt reporting mechanism; set to **1b** for latching the interrupt event until an user-controlled clearing event occurs.

POL: Polarity field – controls the polarity of the active state of the INT pin; set to **0b** for active-low INT polarity.

ME: Mask exponent field – forces the Result Register exponent field to zero and available only in the manual full-scale setting mode; left to **0b** as the reset value.

FC[1:0] Fault count field – sets the number of the consecutive fault events (exceeding levels of the limit registers) to trigger the interrupt reporting mechanism; left to **00b** for one fault as not used.

Low-Limit Register (address = 02h)

Bit number	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Bit meaning	**LE3**	**LE2**	**LE1**	**LE0**	**TL11**	**TL10**	**TL9**	**TL8**	**TL7**	**TL6**	**TL5**	**TL4**	**TL3**	**TL2**	**TL1**	**TL0**
Access type	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W

$\underbrace{}_{}$ LE[3:2] = 11b set by firmware to enter End-of-Conversion mode with the INT pin going active on every measurement completion

Fig.6. OPT3001 register maps and bit descriptions.

Table 3 lists the full-scale range values and corresponding resolutions as a function of the exponent field value. As auto-range mode is used in the device prototype and the ALS IC automatically selects one of the possible resolutions and full-scales depending on illumination level, it has been found to be convenient and useful to display on the LCD panel not only the final illuminance level result, but also information about the resolution of the actual measurement completed.

Fig. 6 displays the content of the Configuration Register, which controls the major operation of the ALS device and is properly set by firmware to the field values (listed in the figure) allowing continuous conversion and display of the illuminance results with the maximum possible accuracy. The Low-Limit Register although not directly used in the proposed device functionality is modified by the firmware to allow a specific End-of-Conversion mode with INT triggering at every completed measurement and so is presented in the register map too.

Table 3

OPT3001 full-scale ranges and resolutions as a function of the Result Register exponent value

E[3:0]	Full-scale range, lx	Resolution, lx
0000b	40.95	0.01
0001b	81.90	0.02
0010b	163.80	0.04
0011b	327.60	0.08
0100b	655.20	0.16
0101b	1310.40	0.32
0110b	2620.80	0.64
0111b	5241.60	1.28
1000b	10483.20	2.56
1001b	20966.40	5.12
1010b	41932.80	10.24
1011b	83865.60	20.48

V. Hardware implementation of the lux-meter device prototype based on the OPT3001 ALS

The detailed schematic diagram of the proposed lux-meter design is presented in Fig. 7. In general it is a microprocessor system build around the 8-bit AT89C2051 microcontroller U1 with the associated components – the quartz crystal X1 and the capacitors C1 and C2 building its clock source and the R1-C3 group performing the initial start-up reset of the circuit. The microcontroller is responsible for four types of tasks including following: communication with the ambient light sensor IC through the I^2C bus, sensor result value calculation and reformatting in ASCII decimal notation, control and representation of the reformatted results on a liquid crystal display and transfer of the results through a serial interface to a remote computer for display and additional processing.

The U3 integrated ambient light sensor OPT3001 communicates with the host microcontroller trough a serial I^2C type interface, consisting of the serial clock signal SCL driven by the P3.5 line of the microcontroller and the serial data SDA bidirectional line connected to the P3.4 line of U1. Reading of sensor data is accomplished in interrupt driven mode when data is available upon conversion end, so the INT-output of the sensor supplies the Interrupt 0 (INT0\) input of the microcontroller with the R4 being the pull-up resistor for the line. Port 1 of the microcontroller (signals P1.7 to P1.0) transfers the ASCII-formatted result data and address information to the U2 liquid crystal display (PC802A or similar 2x8 backlit type). The control signals for the display RS, R/W\ and E are generated by firmware and are supplied through the microcontroller P3.3, P3.0 and P3.7 lines. The display contrast is adjusted with help of the R3 and the P1 potentiometer. The current of the backlight LEDs is limited trough the R2 resistor. The display interface is an industrial standard one with a well-documented and widely used protocol, so every compatible 2x8 display can be used.

The serial interface for connecting the device to a remote computer is build around the U5 integrated circuit MAX232 with the associated components C7, C8, C9 and C10 and the J2 connector. As data transmission occurs only in one direction, from the lux-meter device to the remote computer only the TXD signal (P3.1 of the microcontroller) is actually supplied to the RS232 interface. Remote control of the measurements from the remote computer is not provided, so there is no RXD-line wired. The device prototype does not even use the serial interface at all, so the circuit board is not populated with the respective components, but the firmware developed supports the serial communication.

Two types of voltage supplies are necessary with the proposed schematic – the integrated ambient light sensor circuit U3 expects a 3.3V supply whereas the other integrated circuits are with a normal 5V supply voltage. The power supply module is build around the 3-terminal voltage regulator U6 LM7805 with the associated components C11, C12 and C13 with D1 functioning as the input power supply reversal protective diode and the second voltage regulator U4 TLV71333 [7], the last one transforming the 5V input voltage to the necessary 3.3V. The U4 regulator IC does not need additional capacitors to provide correct functionality in contrast to standard voltage regulator ICs. In the tested prototype device the whole circuitry is supplied with power from a 9V battery and an additional microswitch is provided to switch off the LCD backlight to ensure a longer battery life when not working in dark environment conditions. In the device prototype the OPT3001 sensor is positioned on a separate add-on board with its back to the LCD display, so the light from the display backlight does not interfere with the actual measurements in dark conditions. No such disturbing self-generated noise like effect due to the backlight was observed during the device tests.

VI. Device firmware description

The firmware block diagram is shown in Fig. 8. After initial power-up the hardware initialization

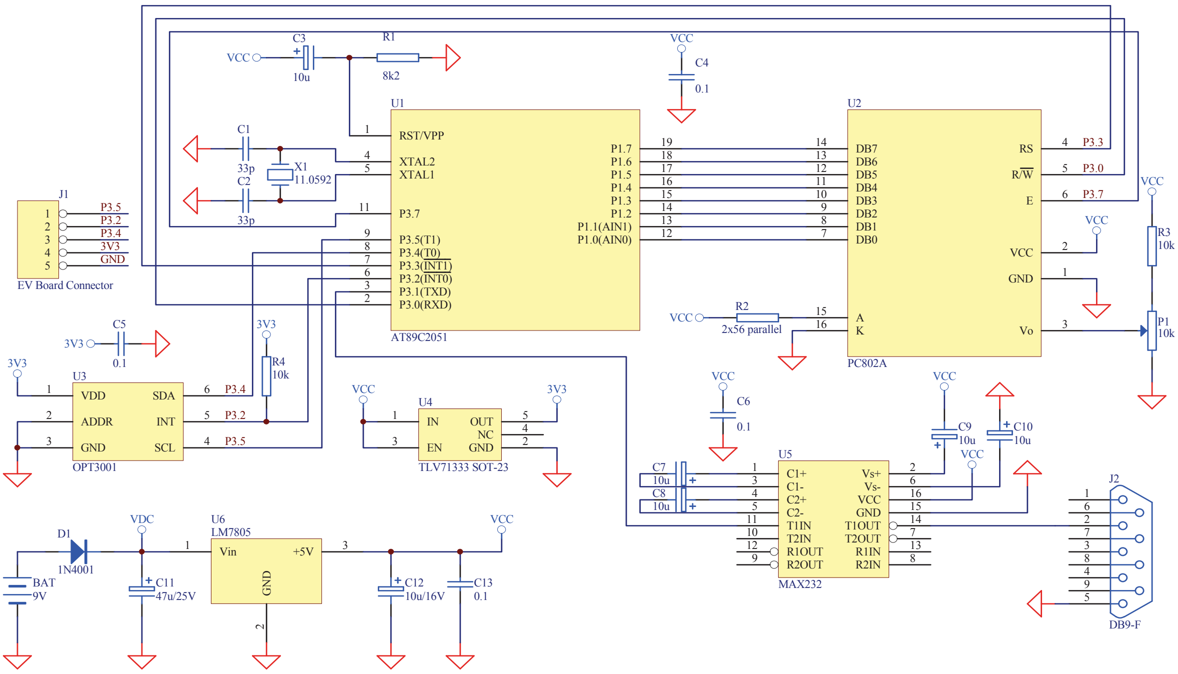

Fig.7. Complete schematics of the OPT3001 based lux-meter prototype device.

occurs governed by the 89C2051 microcontroller. The initialization sequence includes setting up the SCL and SDA lines, the interrupt mode configuration of the processor and the relocation of the stack pointer to an address space, which will not be used by the service routines of the firmware. Initialization of the serial port and the LCD panel follows, performed by the **SerInit** and **LCDInit** subroutines. The initialization of the integrated ALS OPT3001 is next to be done with the microcontroller writing specific values to the two of the internal registers of the sensor – the Configuration Register and the Low Limit Register (the values are shown in the figure). Continuous measurement cycle with 800 ms integration time auto-range mode and interrupt at the completion of every measurement are configured with these values. The **OPT3001_InitialConfig** is the subroutine responsible for setting up the OPT3001. After initialization completes the firmware enables interrupts and enters an endless loop, which it periodically abandons to service the OPT3001-generated interrupts. After every interrupt and before entering the waiting loop again the steps and subroutines described below are sequentially executed.

The OPT3001 Result Register is read with its value being stored in the R1/R0 register pair. This is accomplished by the **LuxMeasurementRead** subroutine. The measurement resolution is extracted from the result exponent field with the resolution being stored in the R3/R2 register pair and the fractional result remaining in the R1/R0 pair. The resolution is converted to ASCII decimal notation and is stored as a string in the internal RAM memory of the microcontroller starting at address 50h. The ASCII string conversion is performed by the **UTIL_BINTOUDEC** subroutine, which converts 16-bit binary integers to a decimal ASCII string. The resolution computed in this way is printed on the LCD first line and is transmitted on the serial port too, which is the **PrintToDisplayI_Line1**, **Message** and **MessageTAB** subroutines task. The final value of the illuminance in lx is calculated with the help of the **UMUL16** subroutine as a multiplication result of the fractional result value and the resolution, the result being stored in binary notation in the R3/R2/R1/R0 registers. The final binary result is converted to ASCII decimal notation and the string is stored in RAM starting at address 50h again. As a 24-bit conversion has to be performed another more specialized subroutine **UTIL_BINTOUDEC24** takes on the task. The converted result ASCII string is printed on the second display line and is transmitted on the serial port too with the help of the **PrintToDisplayI_Line2**, **Message** and **MessageCRLF** subroutines.

During the execution of all conversion and communication subroutines an error check is performed with the **CheckError** service routine to test for missing acknowledgements on the I2C bus for example and for other communication and computational problems too. In the presence of errors interrupts are disabled, an error message is printed on the display (**PrintError** subroutine), a software reset is performed on the OPT3001 (**SoftReset** subroutine) with the code execution being returned to the initial OPT3001setup entry point and normal code execution resumes.

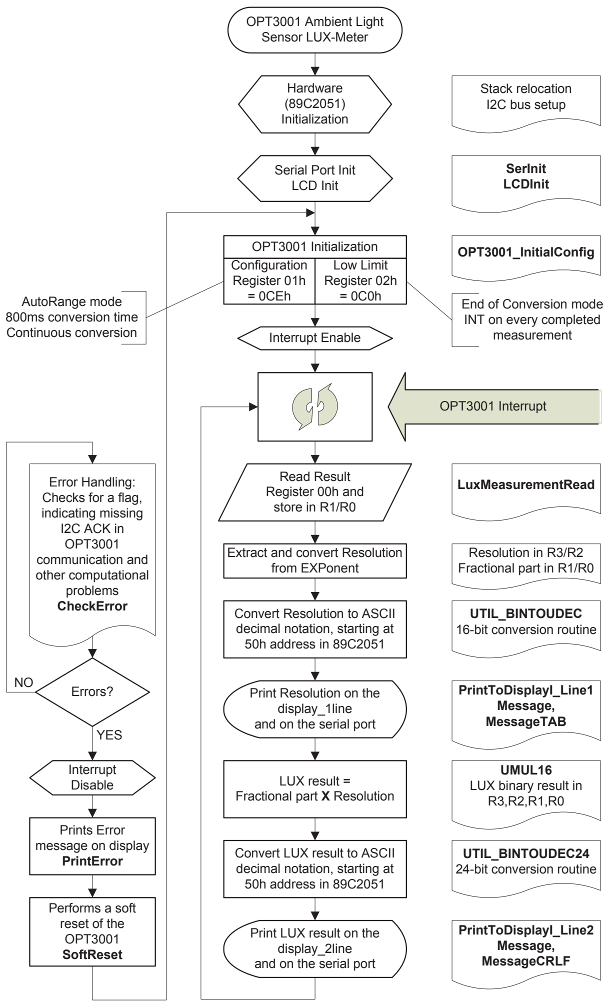

Fig.8. OPT3001-based lux-meter firmware block diagram.

VII. Measurement setup and experimental results

To obtain the experimental results presented in Table 4 and Fig. 9 showing the luminous flux dependence of a high power LED Epistar 1W [8] on the forward current the experimental setup illustrated on Fig. 10 is used. The measurement setup includes a 12V power supply, an adjustable current source with a 0-300mA range, a milliamp meter and the diode under test Epistar 1W.

Table 4

Epistar 1W High Power LED measurement results with the LIMBOX® measurement setup and the OPT3001 LuxMeter

I, mA	Φ_V, lm	A, m²	Φ_V, lm (experiment)	E_V, lx (experiment)
2.00		0.092825	0.88	9.50
3.00		0.092825	1.25	13.50
4.00		0.092825	1.67	18.00
5.00		0.092825	2.09	22.50
6.00		0.092825	2.55	27.50
7.00		0.092825	2.97	32.00
8.00		0.092825	3.48	37.50
9.00		0.092825	3.95	42.50
10.00		0.092825	4.41	47.50
11.00		0.092825	4.73	51.00
12.00		0.092825	5.11	55.00
13.00		0.092825	5.52	59.50
14.00		0.092825	6.03	65.00
15.00		0.092825	6.54	70.50
16.00		0.092825	6.96	75.00
17.00		0.092825	7.43	80.00
18.00		0.092825	7.89	85.00
19.00		0.092825	8.35	90.00
20.00		0.092825	8.86	95.50
25.00	10	0.092825	11.05	119.00
30.00		0.092825	12.72	137.00
35.00		0.092825	14.85	160.00
40.00		0.092825	17.17	185.00
45.00		0.092825	19.12	206.00
50.00	18	0.092825	21.07	227.00
60.00		0.092825	24.69	266.00
71.00		0.092825	29.24	315.00
80.00		0.092825	32.49	350.00
90.00		0.092825	35.27	380.00
100.00	35	0.092825	39.54	426.00
120.00		0.092825	45.48	490.00
150.00	50	0.092825	56.16	605.00
190.00	65	0.092825	66.37	715.00
215.00		0.092825	74.26	800.00
238.00		0.092825	79.83	860.00
250.00	83	0.092825	82.61	890.00
260.00		0.092825	85.86	925.00
280.00		0.092825	91.90	990.00
290.00		0.092825	95.61	1030.00
295.00	98	0.092825	96.82	1043.00

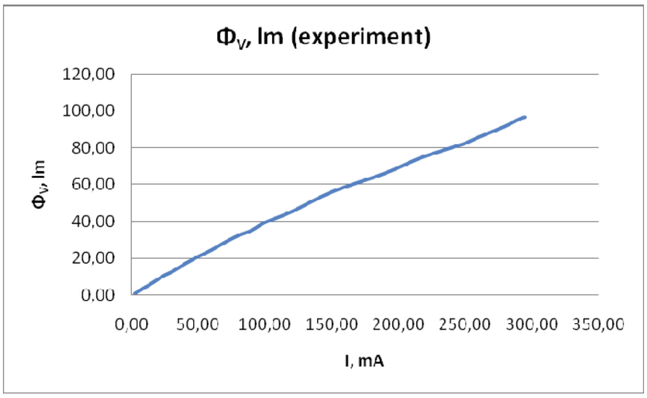

Fig.9. Luminous flux versus forward current dependence.

Because of the extreme heat generation due to the high power nature of the LED it is mounted on a heatsink. The LED OPT3001 based lux-meter system is situated in the LIMBOX® measurement chamber with the following dimensions: height 160mm and a square cross section of 390x390 mm, which complies with the radiation angle of the LED 2θ = 130° taken from the Epistar datasheet. So the whole light spot produced by the LED is located within the bottom side of the chamber without parasitic reflections from the side walls compromising the measurement accuracy. The luminous flux of the LED **Φv** (a parameter given in the device datasheet) and the illuminance level **Ev** at the point the lux-meter is placed (opposite to the LED at the bottom side of the chamber) relationship is given by equation (3)

$$\Phi_V, lm = A \times E_V, lx, \qquad (3)$$

with A being the area of the conical cross section of a sphere with a radius r, equal to the chamber height and a cone angle equal to the LED radiation angle.

This area is computed for the actual measurement chamber dimensions according to the Fig. 9 expression inset with the value being used in Table 4 to relate flux and illuminance levels. As the intensity of the Epistar LED is nearly constant within the whole radiation angle of the device used in the calculations of the illuminated area as evident from the Fig. 11 radiation pattern [8], the equation (3) is applicable to the illuminance level / luminous flux conversion without compromising the accuracy of the setup. Additionally there is a sharp drop in the intensity of the LED outside the radiation angle, so the complete luminous flux is practically taken into account in this measurement setup. The LIMBOX® chamber completely eliminates external light noise preventing ambient light to penetrate to the measurement device.

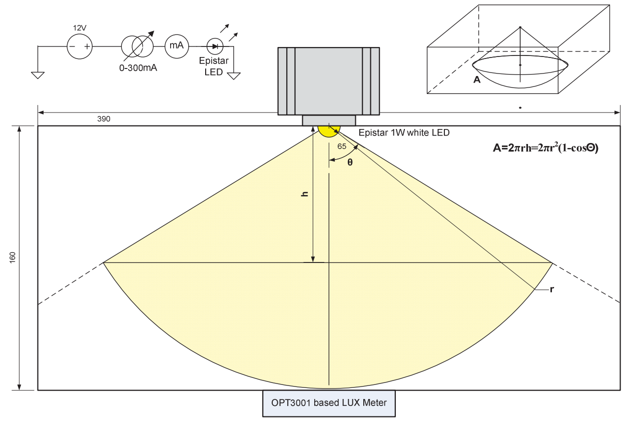

Fig.10. Experimental setup for testing the OPT3001 luxmeter.

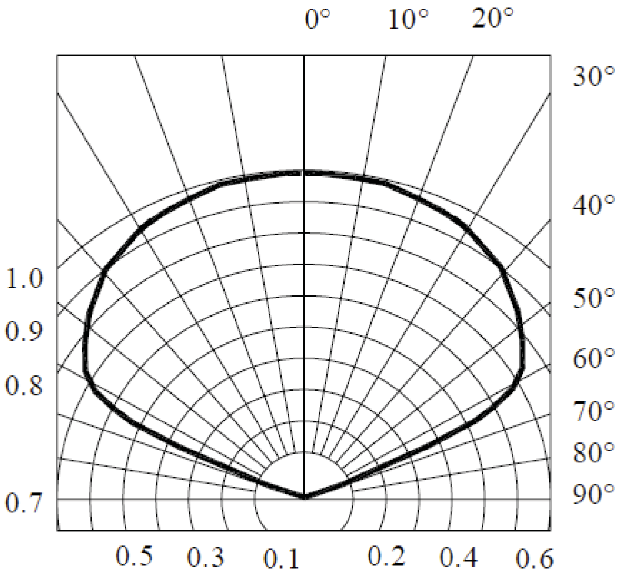

Fig.11. Epistar LED radiation pattern.

VIII. Conclusion

The comparison of the second (scarce flux data from the Epistar LED datasheet) and fourth (much richer experimental data, obtained with device prototype shown in the Fig. 12 photos with the OPT3001 piggybacked board visible) columns in Table 4 clearly demonstrate that integrated ALS solutions prove to be more than adequate for building measurement platforms both as functionality and result accuracy obtainable.

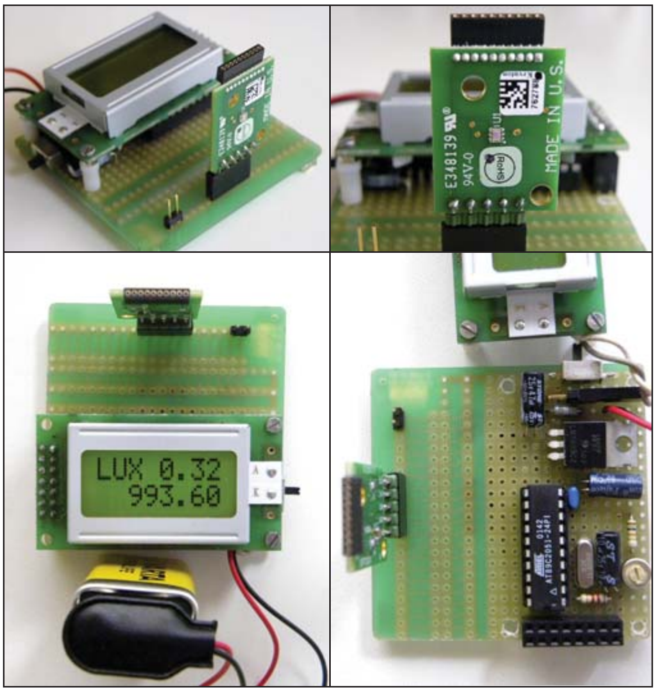

Fig.12 OPT3001 lux-meter device prototype.

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