Research on the power supply of an integrated communication module for a gentelligent component

Dudko, U.; von der Ahe, C.; Overmeyer, L.

Abstract

The research presented in this paper is aimed to analyze the parameters of the given multijunction solar cell as a basic part of power supply unit for a designed transponder, embedded in a gentelligent component (a metallic bolt). The development of the test setup for measuring the solar cell characteristics is the main goal of the study. Since the solar cell output is sensitive to the electromagnetic spectrum and intensity of the light source, it is necessary to define, which artificial light sources can be used to power the device in low-sun or without-sun conditions. The minimal illumination conditions in which the solar cell produces enough power for the whole device operation were also identified. Moreover the methods of improvement of the power supply system efficiency were proposed and implemented.

1 INTRODUCTION

The progress over last decades in miniaturising chips, wireless data transfer technologies and low-power consumption electronic devices made it possible to design component-integrated autonomous sensors. These networks have a big potential for widespread use in maintenance prediction of manufactories, in intelligent building management systems and energy saving smart grids [16].

The sensor becomes self-powering and therefore autonomous. The use of primary batteries instead of grid connections makes the sensor network independent and capable to provide extended operations. However their periodic replacements and disposal present a tough and burdensome task, especially in hardly reachable locations, since the process is expensive and time consuming [14].

The idea of exploiting ambient energy, which is converted into electrical energy, appears to be the best alternative. This concept, which is usually known as energy harvesting, has the following advantages: flexibility, long life-time capability and environmental friendly operation. The ambient energy can be extracted by utilizing thermoelectric effects, vibrations, radio-frequency power transmissions and solar irradiance. However, the tendency of autonomous sensor dimension reduction leads to a low available power from the energy scavenging device. It causes a big challenge to find a balance between the desirable size of a sensor node and the power supply element embedded in it. [1, 2]

1.1 PROJECT OVERVIEW

The SFB 653 (German: “Sonderforschungsbereichs” – Collaborative research center) performs the research in design of gentelligent components. The name combines the meaning of two terms “genetics” and “intelligence”, which denote the ability of the components to recognize dynamic parameters by the integrated sensors and produce the information necessary for reproduction and evolution of the component. In the subproject L2 the gentelligent component presents a metallic work piece with an embedded electronic system (transponder) with the function of data processing, storage and communication. The functional diagram of the communication module is represented in Figure 1. The wireless connection between the reading/writing unit and the transponder is based on the radio frequency identification (RFID) principle. The transponder contains a temperature or a strain sensor, a microcontroller (MCU), a power supply unit (solar cell, diode and super-capacitor), an antenna and a modulator and demodulator circuit.

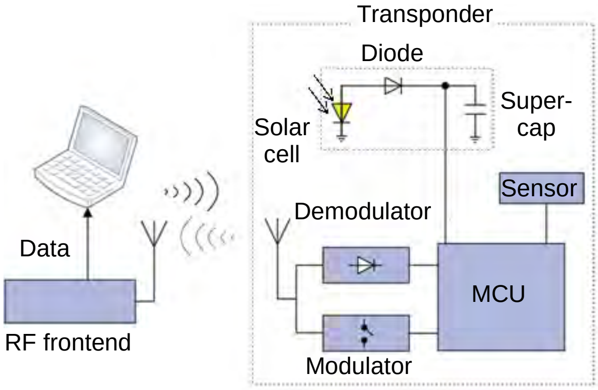


Fig.1 Functional diagram for the communication module

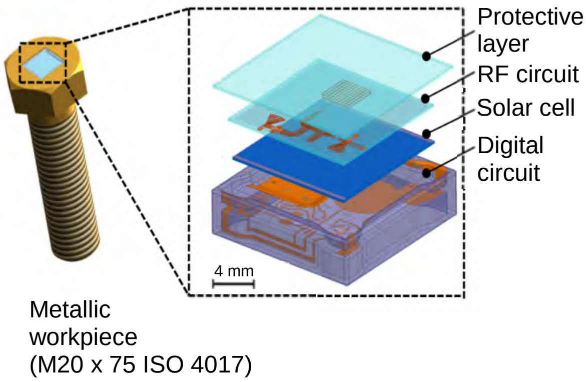


Fig.2 Communication module integrated in the metallic workpiece [3]

The design concept of the device capable of being integrated in the head of the bolt is depicted in Figure 2. The size requirements of such electronic modules are limited to 13 x 13 x 4 mm. [3]

In preliminary research of the L2 project the C4MJ concentrator solar cell produced by Spectrolab with the dimension of 1 x 1 cm was chosen as a power supply unit for the metallic component to harvest the optical energy and to convert it to electrical power. According to the ASTM G173-03 standard, this solar cell reaches efficiency of 40% at 500 suns (50W/cm^2), which essentialy exceeds the other solar cell types [2]. To store the gained energy from the solar cell the supercapacitor connected via a Schottky diode[1] is used (Figure 1). The Schottky diode is necessary to avoid the discharging of the storage unit during the period of darkness. The solar cell is placed under the quartz glass and protective layer on the top of the housing.

To increase the number of use cases, the device must be usable in different light conditions, especially in indoor illumination, where the light is created by a mixture of natural and artificial sources. Indoor light scavenging performs a challenging task, since the levels of available light energy inside buildings are a factor of ~10^4 less than those that can be obtained outside [4]. Therefore it is necessary for the solar cell to be efficient enough to operate under different kinds of electrical lighting. For that reason the characteristics of the given solar cell have to be researched.

[1] Schottky diode is a semiconductor diode with the junction of a semi-conductor and a metal. It has a low forward voltage drop and a very fast switching action.

1.2 THE LOAD REQUIREMENTS

Low power microcontrollers (MCUs) are used in autonomous sensors to process the digital data, to obtain the measured quantity from a digital code and to transmit the measurements, if externally requested. In order to save power MCUs are typically operated in two main power modes: *active* and *standby* mode. In standby mode all the modules (e.g. ADC, analog comparator) are disabled until the MCUs is woken up to process a request [1].

Considering that the given solar cell generates power in the range of microwatts the ultra-low power microcontroller (MSP430FR5738) was chosen. The research on the MCU power consumption for a communication example of the temperature value transmission have been done in the frames of L2 project in [3] and the obtained results are shown in the Figure 3.

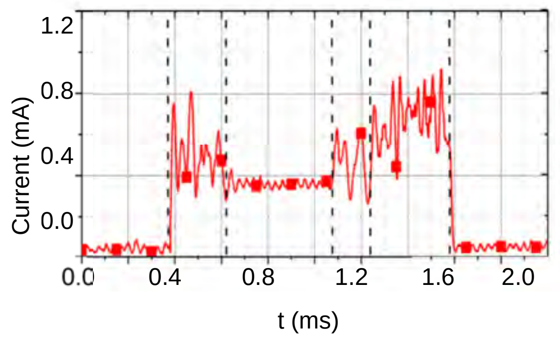


Fig.3 Current consumption of the MCU during the communication flow of the reader for the temperature value request

The presented results show that the consumed current at the lowest possible voltage of 2 V reaches 0.8 mA in active mode and 0.033 mA in standby mode. Thus, the power consumption of the chosen microcontroller in the assembled system varies between 58 μW and 1.7 mW.

The declared current in the datasheet of the microcontroller [13] is 81 μA for active mode and 6.3 μA for standby mode. That means that the MCU operation can be optimized, if necessary. The other research group is responsible for the MCU consumption optimization. The lowest power consumption that can be achieved varies between 12 μW and 0.15 mW.

The paper is organized as follows. In Section 2 the theory about the basic theoretical concepts of light, energy storage devices and multijunction solar cell operation principle is explained. Section 3 is devoted to simulating indoor illumination conditions, measurements of the light power, solar cell characteristics and the results discussion. In Section 4 the two methods of solar cell efficiency are reported and their implementation procedure and results are discussed. Section 5 is devoted to the conclusions and further research ideas.

2 STATE OF THE ART

2.1 PROPERTIES AND CONCEPTS OF LIGHT

The electromagnetic spectrum defines light as a wave with a particular wavelength. A spectrum describes the variation of a specified physical quantity as a function of wavelength.

In order to evaluate light two different unit systems are generally used: radiometric and photometric. Radiometric units refer to the power (in watt) of the total electromagnetic spectrum, while the photometric units deal only with visible parts of it, in terms of its perceived brightness to the human eye, denoted by a luminosity function $V(\lambda)$. The illuminance E_v (measured in lux) is a photometric unit associated with its radiometric equivalent "irradiance" $E_e(\lambda)$ through the following relationship:

$$E_v = K_m \int_{\lambda} E_e(\lambda) V(\lambda) \; d\lambda \qquad (1)$$

where λ is a wavelength and K_m is a constant coefficient, called maximum spectral efficacy (K_m= 683 lm/W).[5]

The conversion of illuminance to irradiance for non-monochromatic light can be performed with the known spectral distribution function $f(\lambda)$ by the following formula [6]:

$$E_e = \frac{E_v \int f(\lambda)\, d\lambda}{K_m \int f(\lambda)\, V(\lambda) d\lambda} \qquad (2)$$

The illumination level inside buildings is designed to achieve satisfactory light conditions depending on the purpose of their use. According to the ISO standard ISO 8995-1:2002 (CIE 2001/ISO 2002) the areas where continuous work is carried out, the maintained work plane illumination level should not be less than 200 lux. Particularly, the maintained illuminance on desks for regular office work is recommended to be in the range of 300-500 lux; for halls and corridors it is specified within a range from 50 to 100 lux [7]. Based on the ISO standard recommendations it was decided to perform the measurements with the illumination of 100, 200, 500 and 1000 lux. The preliminary experiments showed that the measurements at less than 100 lux are inexpedient, since the emitted power at such illumination levels is very low.

2.2 OPERATION PRINCIPLE OF MULTIJUNCTION SOLAR CELL

The solar cells or photovoltaics directly convert the optical energy into electricity. The energy coming on the solar cell surface generates both a current and a voltage. The efficiency of a solar cell is determined as the ratio of incident power P_{in} to the maximal electrical power obtained from the solar cell:

$$\eta = \frac{P_{max}}{P_{in}} = \frac{P_{max}}{E_e A_A} \qquad (3)$$

where E_e is incident irradiance (W/m^2) and A_A is the aperture area of the solar cell.

Nearly all photovoltaic energy conversion is based on semiconductor materials in the form of a *p-n* junction[1]. Efficient, but expensive solar cells can be made out of a range of III-V materials.

The *triple-junction GaInP/GaAs/Ge* solar cell has gained our attention, since it produces an electrical current with an efficiency of up to 40 % in indoor flash test conditions (500 kW/m^2, AM1.5). The energy bandgaps of all three materials (0.66-1.82 eV) cover the whole spectrum range from 350 nm to even 1750 nm. The spectral response for the tested example at 500 sun conditions (50 W/cm^2) is taken from the data sheet and presented in Figure 4.

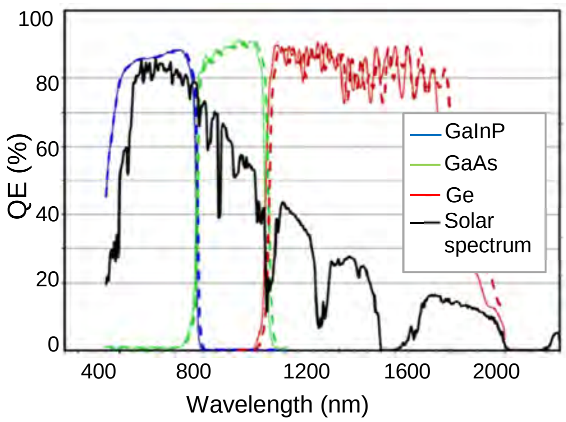


Fig.4 Spectral response for C4MJ solar cell: Quantum efficiency (QE) vs Wavelength [8]

Although, the solution looks promising, the big disadvantage of multijunction technology has to be taken into account: since the three junc-

[1] A junction between n-type and p-type semiconductors

tions are connected in series, the current is clamped by the subcell that produces the lowest current in the array. Therefore all subcells have to be designed to produce equal currents under this specific spectrum. A deviation in the spectrum away from AM1.5[1] will cause one of the subcells to break the balance and to become the current limiter and the overall device efficiency will decrease [9]. Therefore, that fact raises the interest of using multijunction solar cell indoors. Since there is not much research covering this field, several experiments has been done and described in Chapter 3.

2.3 STORAGE ELEMENTS

The power coming from the energy converter (in our case solar cell) is usually not enough for directly supplying a load (e.g. microcontroller in active mode), so a storage element is required to store the energy obtained from the energy harvesting module. There are two types of storage element that can be used: batteries and super capacitors.

Batteries are galvanic cells in which chemical energy from electrochemical reactions is converted to electrical energy that can be harnessed externally. The supercapacitors (called supercaps) consist of carbon electrodes that have very large surface areas and that may be separated by distances as short as in the molecular range. In comparison to the rechargeable batteries supercaps are pollution free, have unlimited charging/discharging cycle, are cheap and have unlimited shelf-life. But at the same time their energy density is one or two orders of magnitude lower than batteries. That means that the rechargeable battery with the same size will work without additional supply much longer. However, the power density of supercaps is up to one order higher than of batteries. Therefore, the charging/discharging rate will be higher for supercaps and it will consume less time to get charged to the required voltage level. [1, 2]

For the current application the supercapacitors were found as more beneficial, since they are straightforward to use and do not require an additional IC for power management, which is necessary for the batteries, since they can be damaged by completely draining them.

[1] The Air Mass (AM) is the path length which light takes through the atmosphere normalized to the shortest possible path length. AM = 1/cos(α), where α is the angle from the vertical (zenith angle). When the sun is directly above, the Air Mass is 1 [11].

3 ANALYSIS OF THE SOLAR CELL EFFICIENCY

3.1 SIMULATION OF THE DIFFERENT CONDITIONS OF INDOOR LIGHT ENVIRONMENT

In order to characterize the given solar cell behavior under typical indoor conditions and investigate its applicability as a power supply for the gentelligent component the actual parameters have been measured under emission of several artificial light sources: Fluorescent (CFL), Halogen, warm and cold LED with illumination levels of 100, 200, 500 and 1000 lux [10]. The characteristics of the lamp samples used in this work are presented in the Table 1.

The given electrical power of the lamp defines the amount of power the bulb consumes from the grid to produce the visible light. Not the entire electrical power is converted into optical power, but only 8-15% depending on the light source. In order to calculate the solar cell efficiency η under artificial light exposure based on (3) the amount of power P_{in} of the light impinging upon the solar cell surface has to be defined.

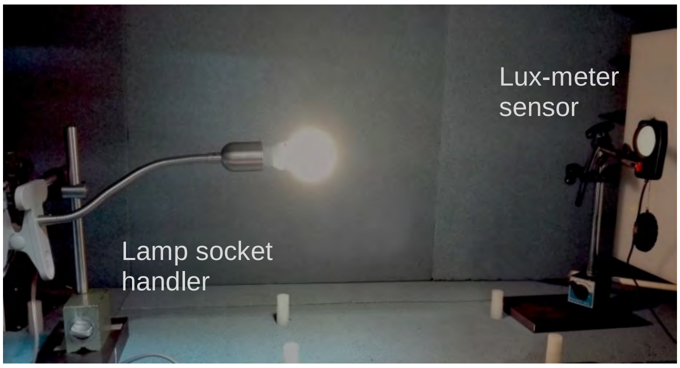
Lamp	Colour temperature	Electrical power	Luminous flux
CFL	2700 K	5 W	200 lm
Halogen	2700 K	20 W	235 lm
LED warm	3000 K	4 W	320 lm
LED cold	6500 K	1.5 W	140 lm

Tab. 1 The given characteristics of the illumination sources used in the work

The direct measurement of optical power with a power meter was substituted with gauging the illuminance of an irradiated surface with a lux meter, since it's low-cost and does not require the additional thermal sensor for polychromatic light. The lux meter (RS-105 Luxmeter mit Photodiode, 50000lx) used in this work has an accuracy of ±4%.

e measurements were performed in an opaque enclosure, as shown in Figure 5.a. The two holders, one with a lux meter sensor photodiode and another one with lamp socket (Figure 5.b) were placed one opposite another over the adjusted distance in such way, that the lux meter readings correspond to the predefined illumination levels of 100, 200, 500 and 1000 lux.

(a)



(b)

Fig. 5 (a) Opaque enclosure and (b) setup for measuring the lamp illuminance (on the picture Halogen lamp sample with measured illuminance of 200 lux)

In the following experiments for measuring the solar cell characteristics the lux meter holder was substituted with a solar cell holder and the lamp was left on the same place for keeping the same distance between the light source and the solar cell to retain the same illumination level.

The conversion of known photometric parameter into radiometric units requires the spectral distribution function of the light emitter to be known [6]. In order to measure the spectrum of the chosen lamp samples the spectrometer (CCS200/M by Thorlabs) was used.

Measurements were performed in an opaque enclosure to eliminate the effect of the ambient light. The spectrum data for every type of lamps is plotted in Figure 6.

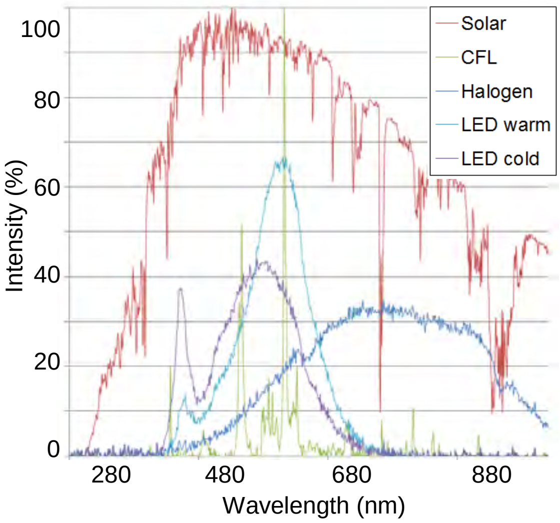


Fig. 6 The measured spectrum of the samples of CFL, Halogen, warm and cold LED in comparison with solar irradiance AM1.5

Comparing the results for each light source with the solar irradiance AM1.5 shows that the deviation in the spectrum of every light source is fairly away from AM1.5. That will cause the significant decrease in the efficiency of the solar cell.

The light power exposing the solar cell surface was calculated by the conversion of the adjusted illuminance E_v to irradiance (with the use of measured spectrum $f(\lambda)$ of the light source) by the formula (2) and then multiplied by the solar cell aperture area. The results are presented in Figure 7.

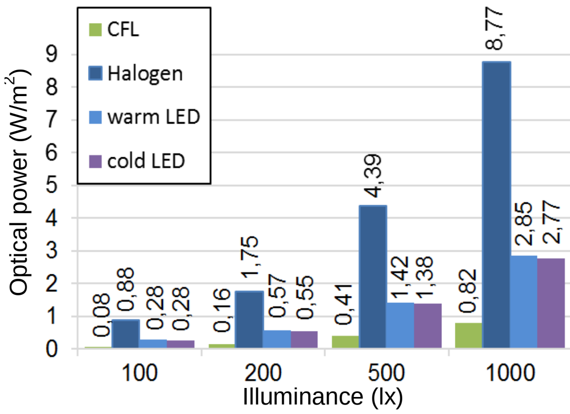


Fig. 7 Calculated optical power for different types of lamps

The obtained results demonstrate that the light power emitted by Halogen lamp has the edge over the other light sources. This is reasonable, because the electrical power of the Halogen sample is also several times greater than of the other lamps.

3.2 MEASUREMENTS OF THE SOLAR CELL CHARACTERISTIC

The measurement setup used for the experiment of measuring the solar cell characteristics is similar to setup for illumination measurements, except the lux-meter sensor is replaced with the solar cell, as shown on the Figure 8.

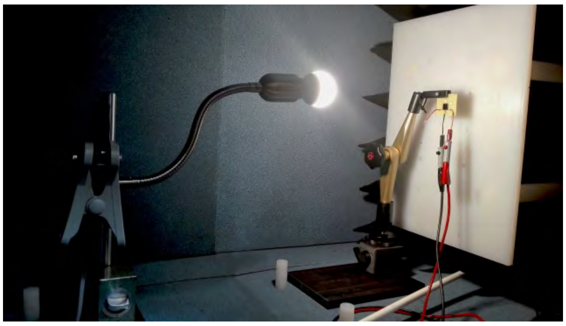


Fig. 8 The experimental setup for measuring I-V curves of the solar cell

The solar cell contacts are connected to a B2912A source measure unit (Keysight technologies) to collect the I-V curves for different measurement conditions.

In Table 2 the values of current and voltage in the point of maximal power of the solar cell (maximum power point or MPP) based on the I–V characterization are reported. As can be seen from the plotts the solar cell response to the Halogen lamp radiation enormously exceeds the response of the other lamps. This happens due to the two facts: firstly, the electrical power of Halogen lamp is initially higher and secondary, its emission with nearly the same intensity covers the whole visible light spectrum and extends far to the infrared range. That brings the Halogen lamp spectrum closer to AM 1.5 conditions, according to which the given solar cell was designed.

Sources		100lx	200lx	500lx	1000lx
CFL	I_{MP}(μA)	1.35	2.49	6.68	15.6
	V_{MP}(V)	1.35	1.32	1.43	1.53
Halogen	I_{MP}(μA)	12.6	27.4	55.19	125
	V_{MP}(V)	1.54	1.63	1.74	1.88
LED warm	I_{MP}(μA)	2.00	3.69	8.71	18.4
	V_{MP}(V)	1.25	1.33	1.44	1.56
LED cold	I_{MP}(μA)	1.05	2.11	4.21	9.33
	V_{MP}(V)	1.22	1.31	1.36	1.47

Tab. 2 I-V characteristics at the maximum power point (MPP) of the solar cell

In the presence of natural light the solar cell responds significantly better. This is shown in Figure 9, where the solar cell characteristics under the mixture of natural and artificial light from an industry hall are marked with the red colour. These measurements were done in the hall on a sunny summer day with illumination level of 500 lx in order to have a general idea of the efficiency of the solar cell exposed to the mixed indoor light, which is the most common case for the application of the designed transponder. Nonetheless these measurements cannot be considered universally applicable, since it is impossible to predict the light availability in indoor environments that can be found in typical campus facilities, where the transponder will be used [15]. For that reason only the worst conditions were considered, assuming that there is no sunlight that enters the building and only artificial light sources are available.

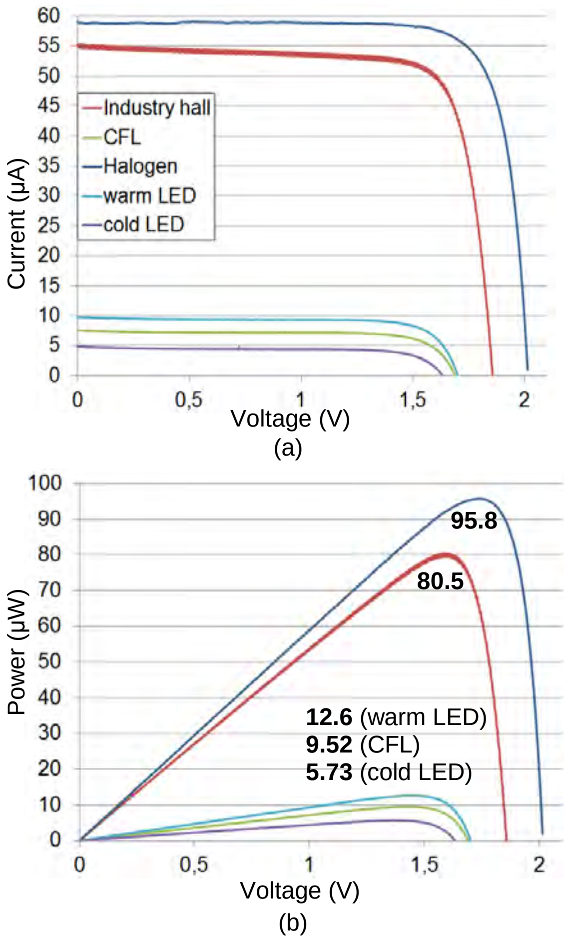


Fig. 9 Comparison of the solar cell response under exposure to mixed light of industry hall and to other artificial light sources: (a) I-V curve and (b) generated power output at 500lx

3.3 RESULTS AND DISCUSSION

The lowest power required for maintaining the microcontroller in not-optimized standby mode amounts to 58 μW and the lowest voltage for its normal operation is 2V. This means that if the voltage from the harvester system falls behind this value the MCU will simply shut down. The data obtained from the experiments finds that these requirements cannot be met with any of the lamps, even under 1000lx illumination. The solar cell generates its highest power output under Halogen lamp emission. Although the generated current achieved by illuminating with 500 and 1000lx ill is enough for maintaining standby mode (>33 μA) of the MCU, the voltage in the maximum power point (MPP) does not reach the value of 2 V.

Knowing the power generated by the solar cell and the power of light impinging on its surface the solar cell efficiency can be obtained by the formula (3). As an example, the following calculations give the resulting efficiency for the illumination level of 200lx CFL lamp:

$$\eta_{CFL} = \frac{3.35\mu W}{0.16\,W/m^2 \cdot 0.989cm^2} = 0.208 = 20.8\%$$

The Figure 10 presents the calculated solar cell efficiency for the other illumination levels:

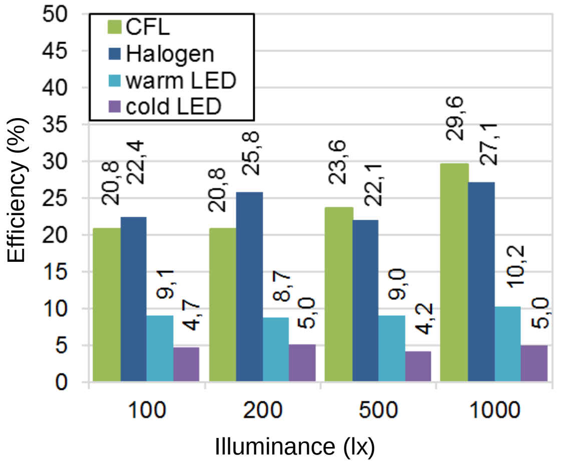


Fig. 10 Solar cell efficiency under different types of lamps and different illumination levels

To summarise the results from the tests of the given solar cell under four types of illumination sources: the device exhibits its highest efficiency under Halogen lamp at low illumination levels of 100 and 200lx. At middle and high illuminance of 500 and 1000lx the solar cell is more sensitive to the light from a fluorescent lamp. In comparison between two LED lamps of different colours, warm LED lamps turned out to be more effective for the solar cell power generation rather than cold LED.

Figure 11 shows that the solar cell efficiency under CFL lamp exposure is similar to the efficiency under Halogen lamp. Nonetheless the CFL lamp cannot be used as an adequate replacement of the Halogen lamp (which is now under sale restrictions in Europe [12]), since the power solar cell generates under the comfortable for human eye illumination conditions (according to the ISO standard) is several times less and not enough to supply the designed transponder.

Since the load requirements are impossible to meet with the standard approach, the following steps to improve the energy supply system were proposed.

4 METHODS FOR IMPROVING THE SOLAR CELL EFFICIENCY

The following two approaches were investigated to improve the efficiency of the solar cells. The first option is to replace the one solar cell with four smaller ones to increase the output voltage. The second method involves the use of additional LED lamps with different wavelengths to cover the whole solar cell spectrum.

4.1 SOLAR CELL ARRAY

The MCU operation time can be increased by increasing the voltage stored in a supercapacitor. The total voltage generated by an array of solar cells that are connected in series is the sum of the voltage generated by a single cell. In order to measure the characteristics of such array a PCB with four small size (5.54x5.54mm) solar cells was designed and tested under exposure of the same light sources and illumination levels as presented in Chapter 3. The examined cells are C3MJ Point Focus concentrators from Spectrolab.

The PCB is shown in Figure 11. The dimension of the overall solar sensitive area is approximately 12x12 mm, which fit the required dimensions of the transponder housing.

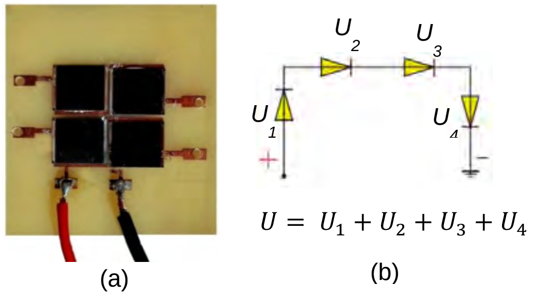


Fig. 11 The solar cell array (a) with its circuit diagram (b)

From Table 3 it can be seen that the obtained voltage from the solar cell array is around 2 - 3 times higher than from the single solar cell. This makes it possible to meet the load requirements of the MCU: under 1000lx illumination, the solar cell produces 4.85V (>2V) of voltage and 42.3μAm of current, which is enough to power the microcontroller in standby mode (>33 μA).

Sources		100lx	200lx	500lx	1000lx
CFL	I_{MP}	0.59	0.86	1.88	3.05
	V_{MP}	4.3	3.71	4.39	3.83
Halogen	I_{MP}	5.42	9.58	26.7	42.3
	V_{MP}	3.83	4.19	4.68	4.85
LED warm	I_{MP}	0.67	0.88	1.58	2.87
	V_{MP}	2.53	2.46	3.43	3.63
LED cold	I_{MP}	0.76	0.88	1.02	1.88
	V_{MP}	2.05	2.46	3.34	3.56

Tab. 3 I-V characteristics of the solar cell array at MPP

Since the solar cells are connected in series the current of the whole array is determined by the smallest current producing cell. For the reason of limited current the total power of the array for some of illumination conditions is less than of the single solar cell (Figure 12). The additional factor that reduces the array efficiency is the losses, accumulated by parasitic resistances with the increasing number of cells in series.

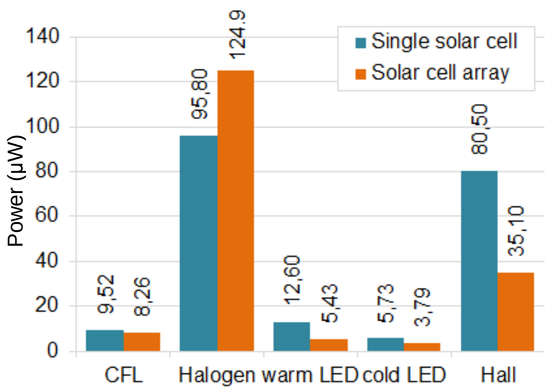


Fig. 12 Comparison of the maximum power output from the single cell and solar cell array at 500lx illumination

4.1 <u>LED SUN SIMULATOR</u>

Since the subcells of the examined multijunction solar cell produce equal currents under the AM1.5 spectrum, deviation away from AM1.5 will cause one of the subcells to break the balance and to become the current limiter. In order to cover the whole spectrum, to which the solar cell responds, designing an additional LED lamp, which simulates the sun spectrum, was proposed.

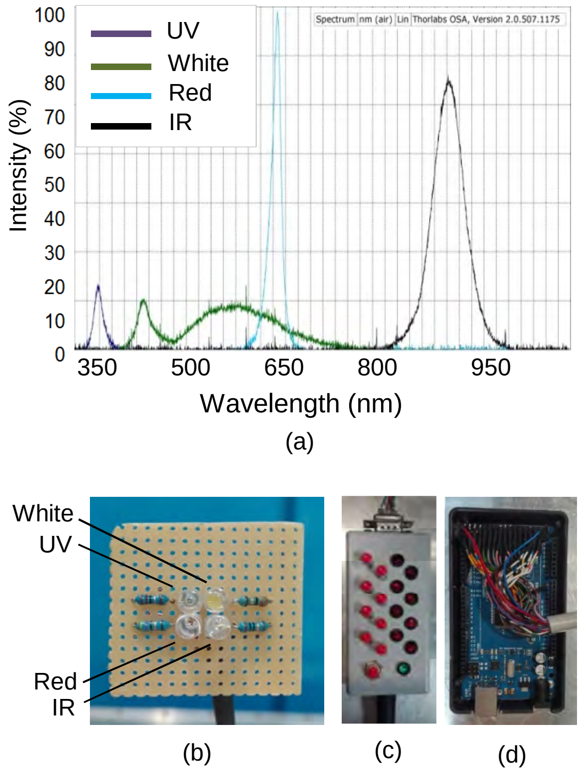


Fig. 13 Spectrum (a) LED sun simulator and the lamp itself (b) with control panel(c) and Arduino board (d)

The simulator consists of four LEDs, which cover the whole wavelength range from UV to Infrared light. The LEDs can be separately turned on/off by the control panel implemented with an Arduino board (Figure 13.b). The designed lamp and the measured spectrum are represented in Figure 13.a.

The measurements were performed with the same experimental setup as described in Chapter 3.2, where the lamp socket setup was replaced with the LED sun simulator, as shown in Figure 14. As can be seen in Figure 15.a the response of the single solar cell on the designed sun simulator is not much different from the response on a white LED or a CFL lamp. The reason for such behavior resides in the spectrum of the Infrared LED which ranges between 800 and 950nm (Figure 13.a), while the AM1.5 spectrum reaches 1800nm in the infrared zone. The Infrared LEDs, which emit in wider range, are currently not commercially available.

However the array of four solar cells shows a rather good efficiency under the emission of the LED sun simulator (Figure 15.b).

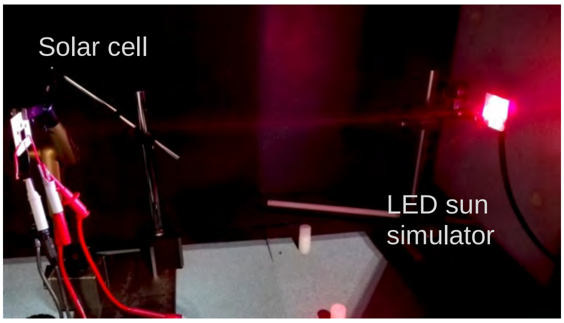
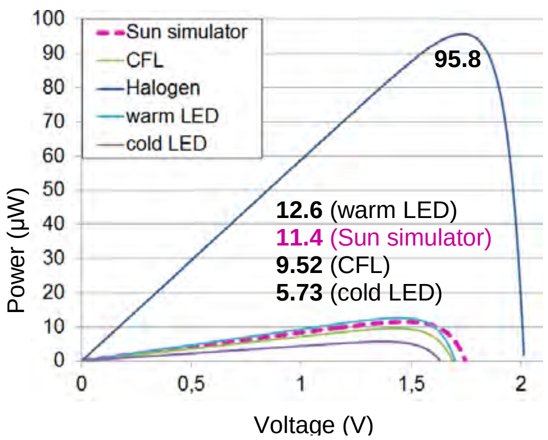
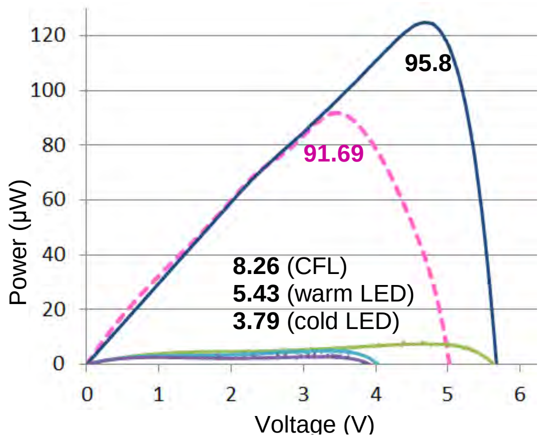


Fig. 14 The setup for measuring solar cell response on the LED sun simulator emission at 200lx

The measured current and voltage results reported in Table 4 demonstrate that under 1000lx illumination the solar cell array can produce 44.4 μA of current and 3.34 V of voltage, which overcomes the MCU restrictions and is enough for powering the transponder.



(a)



(b)

Fig. 15: Output power from (a) single cell and (b) solar cell array under LED sun simulator emission at 500lx

Sources		100lx	200lx	500lx	1000lx
Single SC	I_{MP}	1,69	2.69	7.79	16.2
	V_{MP}	1,29	1.36	1.47	1.59
SC array	I_{MP}	4.77	9.51	26.5	44.3
	V_{MP}	3.15	3.4	3.46	3.34

Tab. 4: Current and voltage in maximum power point of single solar cell (SC) and solar cell array under LED sun simulator emission

5 CONCLUSION AND FUTURE RESEARCH

In this paper the analysis of multijunction solar cell characteristics was presented. The solar cell composes a central part of power supply unit of the communication module embedded in gentelligent component (a metallic workpiece), The size limits of the component (13x13x4mm) set a challenge of harvesting the optical energy by the solar cell of 1x1mm area, which produces extremely low power levels under ambient light.

The accomplished research demonstrates that the required voltage and current for the normal MCU operation of the transponder in no-sun conditions can only be obtained from the array of four solar cells in a room illuminated by a Halogen lamp at 1000lx.

Since the sale restrictions in Europe on Halogen lamp are taking effect, this light source can be substituted with an LED sun simulator, which emission at 1000lx is enough to overcome the MCU consumption restrictions. The LED sun simulator cannot be used as a source for room illumination, as its light is not comfortable for the human eye. However, it can be executed as an additional lamp, which turns on and off periodically charging the transponder energy storage. The evaluation of the time required for illuminating the solar cell by a LED sun simulator for full capacitor charging will be covered by our future research.

The efficiency of the solar cell significantly increases with the presence of natural light. The design of an experimental setup for the solar cell efficiency measurements under natural light performs a challenging task, which can be a possible direction of further investigations.

In this paper the power supply unit consisted of the solar cell, the supercapaciitor and the Schottky diode was considered as a direct-coupled circuit. In order to perform the intelligent power management a special energy harvesting IC can be integrated. The research of the possible use of an energy harvesting IC can be a further step of the solar cell efficiency improvement.

6 REFERENCES

[1] Penella-López, M. T.; Gasulla-Forner, M.: Powering autonomous sensors: an integral approach with focus on solar and RF energy harvesting, Springer Science & Business Media, 2011.

[2] Beeby, S.; White, N. M.: Energy harvesting for autonomous systems, Artech House, 2010.

[3] Dao, Q. H.; Skubacz-Feucht, A.; Lüers, B.; von Witzendorff, P.; von der Ahe, C.; Overmeyer, L.: Novel Design Concept of an Optoelectronic Integrated RF Communication Module, Procedia Technology 26, pp. 245-251, 2016.

[4] Mathews, I.; King, P. J.; Stafford, F.; Frizzell, R: Performance of III–V Solar Cells as Indoor Light Energy Harvesters, IEEE Journal of Photovoltaics 6(1), pp. 230-235, 2016.

[5] Gigahertz-Optic: Tutorial – Basics of Light Measurement, 2016, https://www.gigahertz-optik.de/en-us/news/tutorial-basics-of-light-measurement/ (access date: 01.07.2016).

[6] Shaw, J.: Converting LED photometric to radiometric values, The Electro-Optic (EO) Effect, EELE 482 Electro-Optical Systems, 2012.

[7] Philipps, S.: Current status of concentrator photovoltaic (CPV) technology, National Renewable Energy Laboratory (NREL), 2015.

[8] Spectrolab: CPV Point Focus Solar Cells. C4MJ Metamorphic Fourth Generation CPV Technology, Datasheet, 2011.

[9] Kinsey, G.; Edmondson, K.: Spectral response and energy output of concentrator multijunction solar cells, Progress in Photovoltaics: Research and Applications *17*(5), pp. 279-288, 2009.

[10] Li, Y.; Grabham, N.; Beeby, S.; Tudor, M.: The effect of the type of illumination on the energy harvesting performance of solar cells, Solar Energy 111, pp. 21-29, 2015.

[11] PV Education: Air Mass, 2014, http://www.pveducation.org/pvcdrom/2-properties-sunlight/air-mass, (access date: 03.09.16).

[12] Lumitronix: The Incandescent Light Bulb Ban in EU, 2016, http://www.leds.de/en/The-Incandescent-Light-Bulb-Ban-in-EU/, (access date: 12.09.16).

[13] Texas Instruments: MSP430FR573x Mixed-Signal Microcontrollers, Datasheet, 2016.

[14] Sacco, A.; Rolle, L.; Scaltrito, L.; Tresso, E.; Pirri, C.; Characterization of photovoltaic modules for low-power indoor application, Applied energy 102, pp. 1295-1302, 2013.

[15] Carvalho, C.; Paulino, N.: On the feasibility of indoor light energy harvesting for wireless sensor networks, Procedia Technology 17, pp. 343-350, 2014.

[16] Yinbiao S.; Lee K.; Lanctot P.; Jianbin F.; Hao H.; Chow B.: Internet of Things: Wireless Sensor Networks, White Paper, International Electrotechnical Commission, p.78, 2016.

Author:	Dudko Uliana von der Ahe Christoph Overmeyer Ludger
University:	Leibniz Universität Hannover
Department:	Institut für Transport- und Automatisierungstechnik