Analysis of Visible Light Communication System for Implementation in Sensor Networks

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Abstract— **Visible Light Communication technology today provides an opportunity for high speed and low cost wireless communication. In this paper, we give solution and research results relating to the VLC application in sensor networks in IoT systems.**

Keywords- Internet of Things; Optical wireless communications; Visible Light Communication; Light Emitting Diode; Sensor Networks.

I. INTRODUCTION

If we take into account the concept that underpins the current topical Internet of Things (IoT) as well as predictions that by the year 2025 there will be around a trillion (10^{12}) Internet connected smart devices, it becomes clear that the existing capacities in Radio Frequency (RF) part of electromagnetic (EM) spectrum for wireless communication is insufficient. In recent years, interest in Optical Wireless Communications (OWC) as a promising complementary technology for RF technology has gained new momentum fueled by significant deployments in solid state lighting technology. The light OW communications is lately gaining more and more on importance. In addition to wider bandwidth and energy efficiency it brings and what the most important, and that is that there are no negative impacts on human health and the environment.

The demands placed upon communications systems designed to support IoT are:

- Affordable price.
- Quality and reliability.
- Safety.
- Low power consumption.

If we consider the prediction of the number and the requirements of future smart devices it becomes clear why is required network communication standard that would allow a relatively short distance, local connect to as many devices. It is logical that smart devices in sensors and machines primarily achieved local communication among themselves, thereby ensuring their primary functions in a space. If we assume that in the small area may be located several tens, hundreds or perhaps even thousands of devices that need to receive and send information, it becomes clear why the existing wireless radio systems will not be able to meet the upcoming requirements.

Modern wireless communication systems based on the IEEE 802.11 family of standards, operating in the unlicensed ISM (Industrial Science Medicine) RF bands. Table 1 provides an overview of the ISM bands in accordance with ITU Recommendations.

TABLE I THE ISM BANDS

Lower freq.	Upper freq.	Frequency range
26.957 MHz	27.283 MHz	0.326 MHz
40.66 MHz	40.70 MHz	0.04 MHz
443.05 MHz	434.79 MHz	1.74 MHz
902 MHz	928 MHz	26 MHz
2.400 GHz	2.500 GHz	0.1 GHz
5.725 GHz	5.875 GHz	0.15 GHz
24 GHz	24.25 GHz	0.25 GHz
61 GHz	61.5 GHz	0.5 GHz
122 GHz	123 GHz	1 GHz
244 GHz	246 GHz	2 GHz

But no matter what not licensed RF bands you are using they are regulated in terms of restrictions on output power and modulation methods (depending on the region where the country is, the device that is used as the RF range). Individual users do not possess the exclusive right to unlicensed RF band because all of them are considered as shared resource. Unlicensed RF bands are not reserved only for devices working under IEEE 802.11 standards, RF bands on 2.4GHz and 5.6GHz are also used for other communication devices such as cordless DECT phones, Bluetooth devices, baby monitors and so on.

However, congestion on ISM RF bands due to the large number of users have an inevitable negative consequence.

The overall width of the available RF channels in the range up to 1GHz on which sensor networks could work is just over 28.106MHz, while in the GHz area intended for operation LAN network, currently in use is around 250MHz. While future standards are expected to use no more than 0.75GHz. Total width of all currently available ISM bands is not exceeding 1 GHz, but with future technologies for use of ≥277GHz it can reach 4GHz.

The Shannon's theorem can give us insight into rough upper limit of capacity that could be achieved by the transfer of information by the total bandwidth available RF channels. For the total bandwidth of all ISM RF channel below 62GHz (802.11a, b, g, n, ac, ad, ah, af; ZigBee, etc.), which is B = 1GHz, the link capacity C for the Signal Noise Ratio (SNR) in the range of 1dB up to 60dB would be in the range from $1x10^{9}$bit/s to $7x10^{9}$bit/s. Conventional methods for capacity improvement, enhanced spatial reuse and inter-cell interference coordination, will not be able to overcome this significant limitation. Therefore, a new communications medium and an alternative technology are required to ever increase the capacity. In this sense, using the OWC systems as an option to traditional RF communication methods and may be used to complement current RF systems, particularly in indoor environments where, according to recent studies, more than 70% of the wireless traffic originates [1], [2].

II. THE VISIBLE LIGHT COMMUNICATION (VLC) SYSTEMS

Another big window for wireles data transmission in the electromagnetic spectrum opens only in the Visible Light (VL) and near Infra-Red (IR) light part of the spectrum in the wavelength range from 1100nm to 300nm. This so-called "optical window" in the near IR area of the EM spectrum represents area free for use, available to everyone and does not require licensing. This area has a width of 800nm, ($7.3x10^{14}$Hz) and extends partially into the IR and Ultra Violet (UV) part of the spectrum with a range of up $2.7x10^{14}$Hz to $1x10^{15}$Hz. Right now there is no technology that would enable us to using the classical electromagnetic oscillating circuits to generate arbitrary frequency and amplitude of the signal in this area, due to that we cannot talk about the opportunities that could bring frequency modulated channel of those dimensions. Therefore we only can assume that if on VLC is applied similar conditions as in the existing RF channels in accordance with Shannon's equation, at a ratio of SNR = 50dB, it can achieve link capacity of about $4x10^{15}$bit/s, which is about $1x10^{6}$bit/s more than currently available in RF.

The technology that we have now is based on the exploitation of natural photonic quantum light emission in semiconductors. Specifically Light Emitting Diode (LED), convert electrical energy into light on the basis of recombination of electrons and holes that release energy quants in the form of photons which have frequency dependent on the material from which the semiconductor layer is made. What can be achieved with them is to be "awaken" (turned on and off) at high speeds, which can be used for directly sequenced coding, part of an orthogonal coding is also possible because on LED’s we can control to some extent the level of photon emission, that is light intensity. In addition, LEDs are available in several different color shades, which allows the application of color separation filters corresponding to the reception so Space Time Coding (STC) be carried applied, i.e. each color can become a separate channel. Light due to its dualistic nature in addition to its quantum also inherent all EM waves characteristics, and can be polarized.

The standard IEEE 802.15.7-2011 foresaw the possibility of the existence of 3 different Physical Layer (PHY) operational mode in which will provide bit rate up to 96Mbit/s for optical clock rate of 24MHz and 16-Color Shift Keying (16-CSK) modulation (PHY III Optical Mode) [3], [4]. As standard provides only a framework, not the technology that they can be achieved, we should mention the project Reasonable Optical Near Joint Access (RONJA), which in 2010 conducted by company Twibright Labs (M.Patočka, K.Kulhavý) where they made the transfer of 10Mbit/s at distances up to 1.4km with one color channel LED application. At the end of 2015. Herald Haas Professor with Edinburgh University introduced the concept of 100Gbit/s network using the diffuse scattered laser beam LEDs in order to reduce the risk to the environment [5].

III. DESCRIPTION AND RESULTS OF EXPERIMENTAL RESEARCH

A. *Criteria for Selection of Components*

Almost all current research in this area is primarily focused on the possibility of applying Hi-Power ≥1W (which are used in lighting), Resonant Cavity Light-Emitting (RCLED) diode, (whose price exceeds several thousand dollars) or diffusely scattered laser LED diodes, with the aim to gain as faster Optical Clock Rate as possible, regardless of the power consumption and cost of assembly. Our research on the other hand focused on the development of sustainable solutions using the widely available technology (preferably more accessible prices) that can be of applied in IoT and sensor systems and whose total power consumption does not exceed 2W (maximum 5W). Taking into account the above guidelines after the initial consideration and experiments we decide not to use ≥1W Hi-Power LED, since their nominal supply current while running is ≈350mA, and pulse at the beginning of the emission cycle goes through 500-550mA. As a substitute in the solution was applied Ultra-Bright (UB) 5mm LEDs designed to work in outdoor daylight condition in signaling devices and large LED panels. UB-LEDs are on the market in average 3 to 5 times cheaper than 1W Hi-Power LED, provide a focused beam of the semi-angle $\varphi_{1/2}$ of 15-30° with the intensity of light emission from 8000 to 37000mcd (mili candela) at Forward current If = 20-25mA (90mW max).

In our measurements of light intensity at a distance of 1m they seemed equal to or better than ≥ 10 times more energy demanding 1W Hi-Power LEDs. In addition only in a very few vendors spec. for UB-LEDs we find information related to "Optic Rise Time" that is $\tau \approx 30$ns (for max power). The Figure 1 and Figure 2 shows the Hi Power and Ultra Bright LEDs respectively.

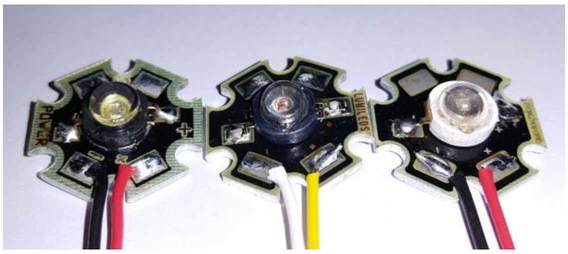

Figure 1. Hi Power LED diode

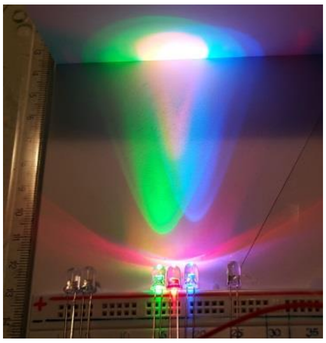

Figure 2. Ultra Bright LED diode

As nominal operating current of used LEDs If = 20-25mA, a voltage range Forward Voltage (Vf) was depending on the color and range from 2.0V to 3.2V (3.6V max.) design appropriate LED driver for 4 to 5 components system was originally based on very fast inverter circuits in bipolar TTL logic from the "F" and "AS" series. The idea was to make system that will provide adequate interface compatible logic level with a minimum consumption of energy resources to the micro-controller, sensor, and the SOC systems. Unlike customized experimental LED systems for transmission and reception available to scientific research institutions, we strictly limited our solution to commercially available and affordable solutions from leading companies in the field of optical, analog and digital electronics, which can be used in development on DIP Breadboard systems.

The cost and complexity are two of the biggest challenges facing IoT implementation on a large scale. The best way to overcome those challenges is to combine multiple functions into a single chip. The IoT System-on-a-Chip (IoT/SOC) brings many functions into one chip. How IoT/SOC solutions should be as accessible and more standard in order to be able to provide mass production, these were preconditions that we have observed and fallow in our design.

For IR transmitter element was taken Vishay Semiconductors IR LED fast TSFF5210 (HS IR), 870nm, with $f_c = 24$MHz, and $t_r = 15$ns, due to higher radiation angle $\varphi_{1/2} = 10°$ relative to their fastest VSLY5850- HS IR LED, 850nm, $t_r = 10$ns with a radiation angle $\varphi_{1/2} = 3°$. On the receiving side, after extensive comparative testing of several fast opto diodes we ware opted for OSRAM Opto Semiconductors SFH 203P, and as an alternative design, we anticipate similar SFH 213. In both cases, the time T_r and T_f (rise and fall time of the photocurrent) are 5ns, but SFH 203P has a much wider acceptance angle of $\varphi_{1/2} = 75°$. The initial selection was BPV10 Vishay photo diode with T_r and $T_f = 2.5$ns and guaranteed photo sensitivity to 250MHz and the angle $\varphi_{1/2} = 20°$ (Vf = 1 to 1.3V, $\lambda = 920$nm, $I_{rev} = 70$uA) but due to less photo sensitive surface 0,78mm^2 and lower efficiency of $\eta = 72\%$ (to 950 nm) it has proved to be less sensitive to color in the visible part of the spectrum in relation to 1mm^2 SFH 203/213 P with $\eta = 89\%$ (870 and 850nm) [6], [7].

B. *Block Diagram of the Transmitter and Receiver*

The Figure 3 shown transmitter and receiver block scheme.

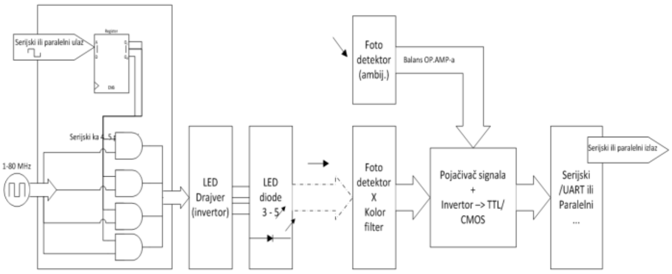

Figure 3. Transmitter and receiver block scheme

The Figure 4 shown scheme of mono channel receiver block with power supply.

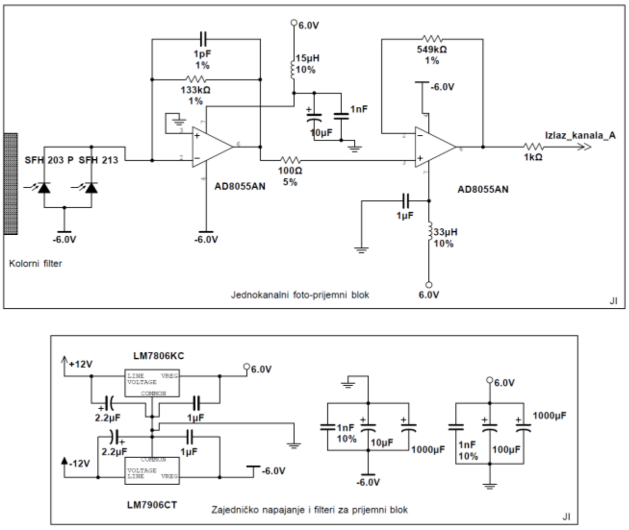

Figure 4. Single channel receivers with power supply

Single-photo block receiver was implemented with very fast 300MHz AD8055AN operational amplifiers (Voltage Feedback Amplifiers) which are characterized by flat frequency response to 40MHz (Gain flatness 0.1 dB). Initially, with the help of tools from the company ADI (Analog Devices Inc.) we designed a two-stage amplifier with ADA4895-2 and ADA4860-1 (SOIC chips) that is supposed to provide a bandwidth of 57MHz for Vp-p = 1V for SHP 203P photo diode [8], [9]. This design was temporarily abandoned due to the limitations of applied technologies and purposes, since IEEE 802.15.7-2011 provides that "Optical Clock Rate" for "PHY III" is F = 24MHz, and what is the cutoff frequency of the applied IR diode. Instead of the those operational amplifiers we opted for solutions that are entailed a combination of available DIP based AD 841, 843, 846, 8055 and other fast circuits O.AMP. We decided to develop solutions based on AD8055AN with two stages, which can be seen in Figure 5.

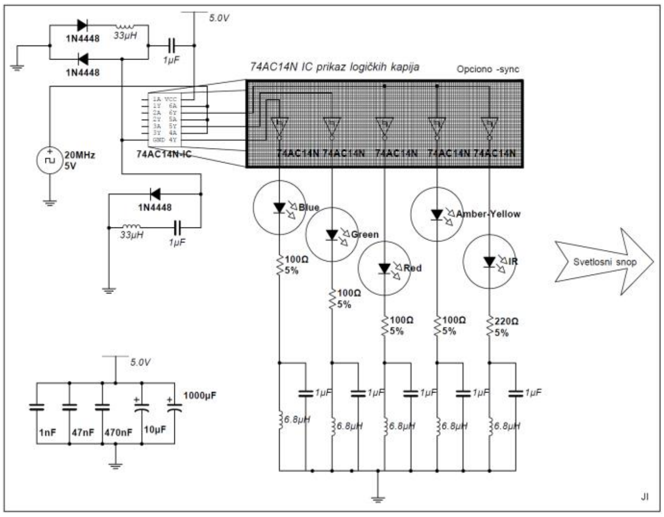

Figure 5. The optimized two-stage transmitted circuit

Parallel tying two photo diode increased input capacity and current in the first stage so that in the second stage takes much less gain, which increases the bandwidth of the applied solutions.

IV. ANALYSIS OF THE RESULTS OF MEASUREMENT

The analysis of 14 different logic circuits with similar function (inverter, non-inverter drivers with or without Schmitt-trigger-a) from different families (AS, ASL, LS, F, HC, HCT, HCU, AC, and ACT) within 74 series, concluded that 74AC14 CMOS Schmitt-trigger inverter circuit with Ioh/Iol = ± 24mA and guaranteed maximum tpd = 9.5ns at 5.0V, will be optimal solution. 74AC14 CMOS IC is characterized by a guaranteed Voh = 3.85V...4.86V Hi-voltage output Ioh. = -75mA…-24mA Hi-current rang, and Vol = 0.5V.....1.65V with Iol = 24mA....75mA, which provides good working characteristics for run of several UB-LEDs of different colors with working voltages of 2V to 3.2V (3.6V max), by providing them with a current of 20mA. This CMOS circuit is due to Schmitt-trigger hysteresis function width of 1.6V better resistant to the input signal noise and has a steeper angle i.e. faster response V/µs from 74AC04. During testing and measurements in real conditions under load 3-4UB LEDs 74AC14 was significantly slower than 74AS1004A and 74AS1034A with tPHL/PLH = 2.5ns and 3.5ns, but almost insignificantly from 74F04/14-3.75ns according 3.88ns. On the other hand 74AC14 because of its CMOS operating mode and Schmitt-trigger function follows the shape of the input clock (50%) much better than others under the workload, what can be seen in Figure 6.

Due to the limitations of the applied operational amplifiers, development environment and available instruments (USB oscilloscopes DDS140 100/200MSPS 8-bits) in the current configuration we can reliably verify the performance of 24MHz transmission pulse at each of color channels. Given the limitations of IR transmitting diode for now we can assume that the Optical clock rate greater then 24MHz or more is possible.

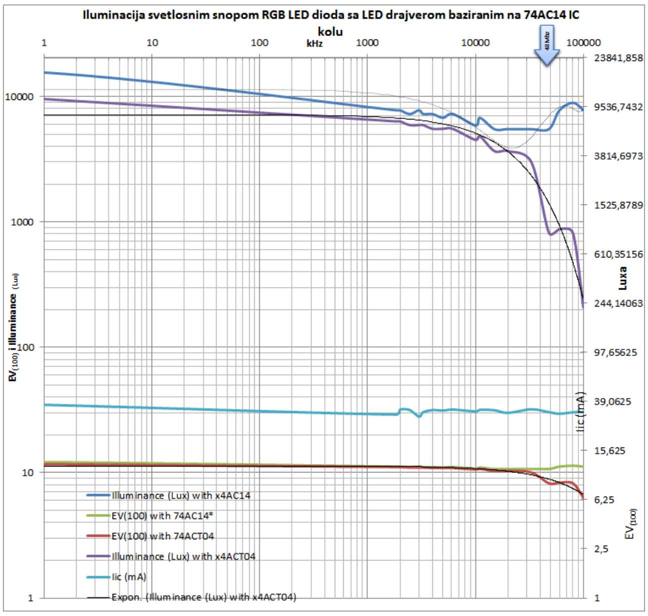

Figure 6. The results of measurement of light intensity over freq. range

By monitoring the light intensity LEDs with increasing frequency in the graph shown in Figure 6, we can see the emergence of a breakpoint after 48MHz as rise in illumination of LEDs. After that point apparently leads to disruption of the symmetry of the signal i.e. increase in the length of the positive periods of the cycle for more than ~ 50%. What speaks to the fact that LEDs are still transmitting interrupt signal, but it is possible that "Optic Rise Time" - τ ≈30ns and probably similar duration of the optical discharge (capacity) excited photons longer.

The ratio of the relative spectral sensitivities SFH 203 photo-diode with respect to the spectral-frequency distribution used Ultra Bright LEDs and IR LEDs in the proposed VLC 4-5 channel system is shown in Figure 7.

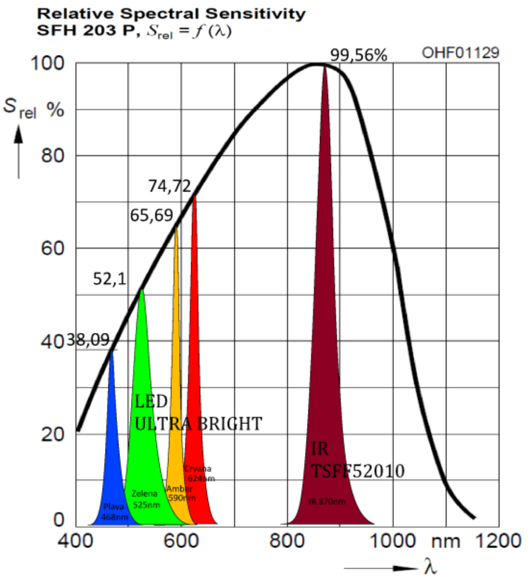

Figure 7. Relative spectral sensitivity SFH203 in correlation to used LEDs

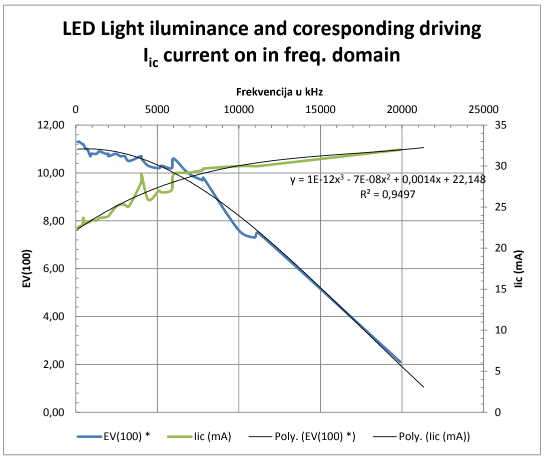

Figure 8. LED light luminance and I_{ic}

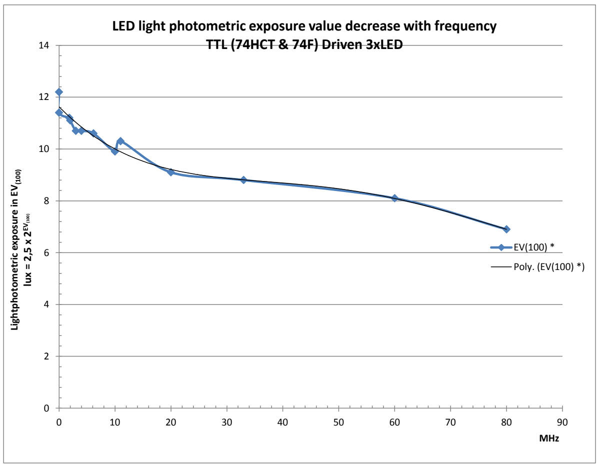

Figure 9. LED light exposure value

The graphical representation of the relation betwen lighting UB-LEDs, working frequency and the current drawn by the LED driver based on 74HCT04 and 74F04/74F14 with 3 LED are shown in Figure 8. and Figure 9.

The decline in the quantity of light as a function of frequency for the LED driver launched by 74HCU04 CMOS inverter IC-circuits (un-buffered - HC04 oscillator version) is shown in the Figure10. To generate the operating frequencies we used exact crystal generators CMOS/TTL clock generator (TCXO-circuit)

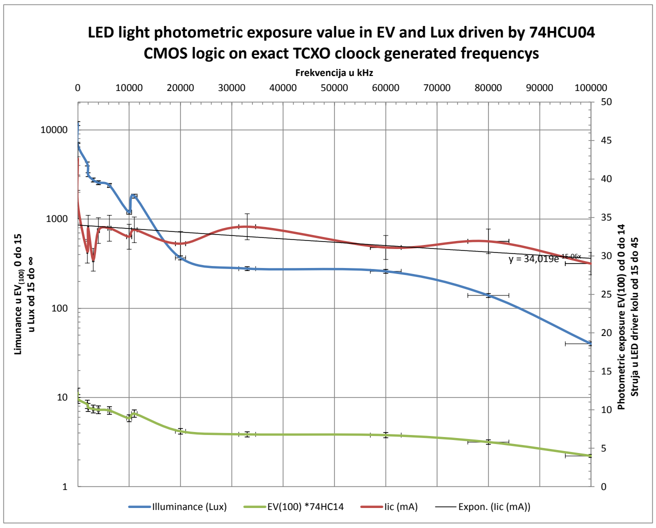

Figure 10. The quantity of light as a function of frequency for the LED driver

The Table II shows the results of measurements of intensity of light emission UB-LEDs in the function of the excitation clock frequency for the final solution of LED driver (fig.5) with filters and fast 74AC14N CMOS IC circuit.

TABLE II RESULTS OF MEASUREMENT OF LIGHT EMISSION INTENSITY UB-LEDS IN THE FUNCTION OF THE EXCITATION FREQUENCY CLOCK

No.	**Frequency. (kHz)**	**$EV_{(100)}$ with 74AC14**	**$EV_{(100)}$ with 74ACT04**	**Illuminance (Lux) with x4AC14**	**Illuminance (Lux) with x4ACT04**	**Remarks**	**I_{ic} (mA)**
1	0.001	12.7	12.6	16634.93	15520.94	*0Hz-ON*	42.65
2	1	12.6	12.1	15520.94	10974.96	*1KHz*	36.7
3	1843.2	11.6	11.5	7760.469	7240.773	*TCXO…*	30.6
4	2000	11.6	11.5	7760.469	7240.773	…	33.6
5	2457.6	11.5	11.4	7240.773	6755.881	…	33.3
6	3000	11.6	11.4	7760.469	6755.881	…	29.5
7	3276.8	11.5	11.4	7240.773	6755.881	…	32
8	*4000*	11.5	*11.3*	7240.773	6303.459	…	33.3
9	*5000*	11.4	*11.3*	6755.881	6303.459	…	33
10	*6144*	11.5	*11.3*	7240.773	6303.459	…	33.6
11	*10000*	11.2	11	5881.336	5120	…	32.5
12	*11000*	11.4	11.1	6755.881	5487.48	…	33.4
13	*15000*	11.1	10.7	5487.48	4158.732	…	33.2
14	20000	11.1	10.7	5487.48	4158.732	…	31.6
15	33000	11.1	10.4	5487.48	3377.94	…	33.8
16	48000	11.1	8.5	5487.48	905.0967	*.6EV@1m*	32
17	60000	11.6	8.6	7760.469	970.0586	…	31.1
18	80000	11.8	8.5	8914.438	905.0967	…	31.9
19	100000	11.6	6.5	7760.469	226.2742	…	32

We measured the illumination of joint light beam of 3 Ultra bright LEDs (Red, Blue, and Green) at the focal point distance of 12cm. Clock frequencies was generated by the discrete TTL / CMOS crystal clock generator with accuracy of $1x10^{-6}$ of nominal value and half period relations of 50%.

V. CONCLUSION

In this paper, we presented made solution, and propose measurement setup for research using the widely available technology (preferably more accessible prices) with the possibility of applying the same in IoT and sensor systems and whose total power consumption does not exceed 5W.

The results obtained in the current configuration can reliably verify the performance of 24MHz transmission pulse at each of color channels. Given the limitations of IR transmitting diode for now we can assume that the Optical Clock Rate greater then 24MHz is possible.

Based on the obtained results it can be concluded that the developed system is able to ensure the data transfer of up to 100Mbit/s using 4-5 channels over short distances and has the potential for further development. It should be noted that the total consumed energy the whole of the system is less than 1W, which gives the possibility of applying battery power supply. Thus, further study will focus on optimizing system layout as well as to achieve a higher transfer data rate. Research will be continued.

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