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Citation: Galal, Mariam, Ng, Wai Pang, Binns, Richard and El Aziz, Ahmed Abd (2020) Characterization of RGB LEDs as Emitter and Photodetector for LED-to-LED Communication. In: 2020 12th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP 2020). IEEE, Piscataway, pp. 385-390. ISBN 9781728160511, 9781728167435

Published by: IEEE

URL: https://doi.org/10.1109/CSNDSP49049.2020.9249617 <https://doi.org/10.1109/CSNDSP49049.2020.9249617>

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Characterization of RGB LEDs as Emitter and Photodetector for LED-to-LED Communication

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Abstract——**Visible Light Communication (VLC) has rapidly grown over the last decade. However, unlike RF technologies, VLC has a simplex channel since two different devices are used for transmitting and receiving. This increases the cost and complexity of the transceiver circuit when a bidirectional link is required. LED-to-LED communication is a potential solution for a half-duplex channel. It utilizes the LED as photodetector for detection. This paper practically examines the RGB LED characteristics with emphasis on responsivity, wavelength sensitivity and angular response. The LED photodetector has a bandwidth of 6 MHz, responsivity of 256 nA/mW and FWHM of 18°.**

Keywords— Visible light communications, LED-to-LED communication, RGB LED photodetector, responsivity, bandwidth

I. INTRODUCTION

Visible light communication (VLC) has gained popularity over the last decade due to the increased demand for smaller communication cell sizes, secure green communication and out-of-the-box solutions for the "spectrum crunch". In the era of Internet of Things (IoT), VLC seems to be an appropriate technology for connecting smaller devices because it depends heavily on light emitting diodes (LEDs) as transmitters, which are the heart of the energy-saving illumination in all residential and commercial indoor environments [1]. VLC is also inherently secure because light is confined within the walls of a room. This prevents eavesdroppers from hacking the network, which makes it a viable option for utilization in RF sensitive environments such as hospitals and airplanes [2].

Despite its many advantages, one of the areas where VLC is lagging is its simplex, one directional channel: the devices on the channel ends are not identical, as is the case with the RF antennae that act both as transmitters and receivers. While the transmitting end of the VLC channel is occupied by an LED, a photodiode is used at the receiving end. In order to achieve a bidirectional VLC link, another set of LED-photodiode combination is required. This increases the cost of the entire system, complicates the driving circuits and is a negative point in space-limited applications.

An LED-to-LED communication system takes VLC a step closer to competing with RF technologies. Due to the physical structure of the LED as p-n junction, it can be utilized as a low-sensitivity *p-n* photodetector as well as a light sensitive capacitor. The idea of employing an LED as photosensitive device is not new. The LED has been previously employed by Miyazaki et. al. [3] as wavelength selective photodetector for ambient light as well as by Dietz et. al. [4] as a very low-cost light sensing device. Later, researchers at Disney research labs proposed an LED-to-LED communication system based on the same technique for toy-to-toy communication [5]–[8]. These researches concentrate on the ability of the LED to store energy. At the start of the receiving bit, the LED parasitic capacitor is charged to its maximum and exposed to the incoming data-carrying light signal. During the detection time, the LED capacitor loses its stored energy faster if light is detected (bit 1) than when no light is detected (bit 0). The transmitter and receiver circuits are synchronized via software and redundant bits to guarantee successful transmission at data rates up to 1 kbps over small distances. While this technique allows successful detection of on-off-keying (OOK) modulated light, it results in very low data rates because of its high dependency on the charging and discharging of capacitors. Kowalczyk et. al [9], [10] on the other hand claim that the choice of the right LEDs in combination with appropriate modulation and equalization techniques can increase the data rate of the LED-to-LED channel to 100 Mbps, employing a transimpedance amplifier (TIA) and no optical concentrators. Similar results were achieved by Chun et. al [11], who achieve a sum data rate of 110 Mbps employing discrete multitone modulation (DMT) as well as an array of large area, high brightness LEDs for transmission and reception. Those LEDs however are not only of large area, but also are very expensive and therefore along with the complex modulation unsuitable for simple inexpensive IoT devices.

The previously mentioned researches prove the potential of some LEDs to act as dual-functionality devices: transmitters and receivers. In order to maximize the performance of the LED as photodetector, its characteristics need to be practically tested to achieve its full photodetection potential. The understanding of the limitations of the LED photodetector leads to optimizing the design of the transmitter and receiver circuits, targeting an LED-to-LED communication system that can compete with current dual simplex channel VLC systems. In their paper [12], Kowalczyk et. al studied some high brightness single colour LEDs and demonstrated the effect of reverse biasing them on their bandwidth. In [13], the same authors studied the wavelengths best detected by each single colour LED and proved that the bandwidth of the LED as photodetector is much higher than its modulation bandwidth. Therefore, they employed a high intensity laser diode (LD) of varying wavelengths to measure the respective response of the LED photodetector. Their research proves that reverse biasing near the maximum point improves the bandwidth of some LED photodetectors while all white LEDs remain unresponsive to the incoming light due to their phosphorus coating.

The previous research aiming at characterizing the LED as photodetector concentrated on single colour LEDs, especially expensive, large are and high brightness non-white LEDs, but never tested the characteristics of an off-the-shelf cheap red-green-blue (RGB) LED. This type of LED is widely used in many applications due to its small size and very low cost as well as its ability to not only produce white light, but also produce a wide range of light colours through light mixing. This paper focuses on practically characterizing an off-the shelf RGB LED as both a transmitter and as photodetector with the aim of determining the compensation points to be considered when designing the transceiver circuit of an LED-to-LED communication system. All experimental tests performed in this paper employ an LED as transmitter, which will be the real transmission device in an LED-to-LED channel as opposed to a laser diode. Moreover, this research aims to fill the gap of characterizing the angular response of the LED photodetector to incident light and practically measures its full-width-half-maximum. It also studies the optimum combination of transmitter and detector sub-LEDs of an RGB LED as well as test the responsivity of RGB LEDs not only at different reverse biases but also experimentally proves that an LED can even detect light when it is slightly forward biased.

II. P-N JUNCTIONS AS LIGHT EMITTERS AND DETECTORS

An LED consists of a *p-n* junction made from a direct bandgap material, such as Gallium-Arsenide (GaAs). When a *p*-type material and *n*-type material are placed next to each other, a *p-n* junction (or a diode) is formed. Due to the high electron concentration on the *n*-side and the high hole concentration on the *p*-side charges diffuse to the opposite sides, resulting in a recombination near the junction. This recombination forms a charge-free depletion region between the *n*- and *p*-sides, resulting in a built-in potential V_0 [14]:

$$V_0 = \frac{kT}{e}\ln\left(\frac{N_a N_d}{n_i^2}\right) \tag{1}$$

where k is Boltzman's constant, T is the temperature, e is the charge of the electron, N_a is the concentration of acceptor dopant atoms, N_d is the concentration of donor dopant atoms and n_i is the intrinsic carrier concentration of the semiconductor.

When a forward voltage V is applied to the *p-n* junction, the built-in voltage is reduced to $V_0 - V$. This narrows the depletion region, until it vanishes completely at $V = V_0$. Recombination increases due to the vanishing electric field and energy is released in the form of photons. The energy E of the released photons is nearly equivalent to the bandgap energy E_g of the semiconductor material and determines the wavelength λ of the emitted photons:

$$E = \frac{hc}{\lambda} \tag{2}$$

where h is Planck's constant and c the velocity of light. If λ is between 400 and 700 nm the emitted photons are perceived as visible light by the human eye [15].

When a *p-n* junction is reverse biased with a voltage V_R, the built-in voltage increases to $V_0 + V_R$ and the depletion region becomes wider. When an incoming photon of energy E falls on the depletion region of the *p-n* junction, it provides energy to the free charges to move to the opposite side of the junction. If its energy is larger than or equal to the energy gap, an electron can be stimulated to move from the *n*- side to the *p*- side, causing a small photocurrent to flow through the device. The more the incoming photons, the higher the produced photocurrent. The generated current is therefore proportional to the radiation power, until saturation is reached. The *p-n* junction is hence turned into a light sensing device, a.k.a. a photodiode. This proves that - in theory - an LED can operate as a photodetector under no or reverse bias if the incoming photons have the energy to penetrate the LED material and stimulate the electrons into higher energy levels [14].

Commercial photodetectors are optimized for light detection with an intrinsic (*i*) layer between the *p*- and *n*-materials with controlled thickness in order to increase the sensitivity, photodetection area, penetration probability of the photon, responsivity and speed of the photodiode. Hence, the *p-i-n* photodiode is expected to be much better equipped for light detection compared to the *p-n* junction of the LED with the disadvantage of the much higher price tag and the inability to produce light when forward biased [14].

The *p-n* and the *p-i-n* have a parasitic capacitance which results in a delayed or slow AC response and hence a limited bandwidth when used for communication. The bandwidth of a photodetector is related to its capacitance [15]:

$$BW = \frac{1}{2\pi R_{load} C_j} \tag{3}$$

where BW is the bandwidth, R_{load} is the load resistance and C_j is the junction capacitance. To increase the bandwidth, the junction capacitance needs to be reduced by increasing the reverse bias voltage.

RGB LEDs consist of 3 sub-LEDs which emit red, green and blue light respectively. The sub-LEDs have a common terminal (anode or cathode) and can be driven separately via their other terminal. Although RGB LEDs emit relatively narrow spectrums around the three primary colors, the human eye perceives the emitted light as white when all 3 sub-LEDs are lit with the right power ratios. While RGB LEDs are the less used option in creating white light due to their higher cost and more complex driver design, they are optimum for the dual functionality of transmitting and sensing light. Unlike phosphor-based LEDs, RGB LEDs can detect light signals on their sub-LEDs separately, have a much faster response and inherently allow wavelength division multiplexing (WDM) [16]. That is why off-the-shelf 5 mm common cathode RGB LEDs (Kingbright®) are employed throughout the experiments of this paper [17].

III. EXPERIMENTAL SETUP

All experiments in this paper are performed in a dark room and repeated with five different samples of off-the-shelf common cathode RGB LEDs [17]. The results are the average of all five measurements.

A. Measuring the parameters of an LED as transmitter

This section aims to propose an experimental setup to practically characterize the LED as light emitter. In this instance, the magnitude and peak wavelength of the optical power emitted by each sub-LED, as well as the linearity of the emitted optical power relative to the current driving the LED.

The experimental setup shown in Fig. 1 is used to measure the light power and spectrum emitted by the RGB LEDs under

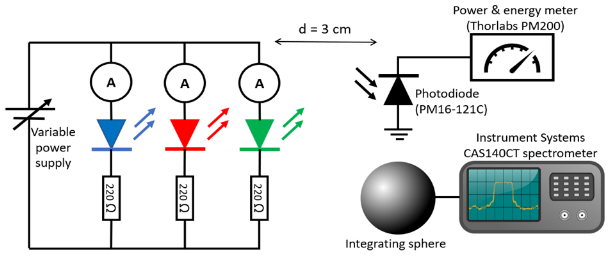

Fig. 1 Experimental setup for measuring the optical power & spectrum of RGB LED transmitters

test. The sub-LEDs are forward biased by connecting each to a 220 Ω series resistance to a variable power supply. At a distance of d = 3 cm, a high sensitivity calibrated silicon PIN photodiode (PM16-121C) is attached to an optical power and energy meter (Thorlabs PM200) and is directly facing the RGB LED. The light power is measured at different supply voltages. When each sub-LED is supplied by 20 mA DC current - the recommended value of current for the sub-LEDs according to the manufacturer's datasheet - the spectrum of the light emitted by the LED is measured using a spectrum analyser (Instrument Systems CAS140CT spectrometer with integrating sphere). The peak wavelengths of each colour as well as the full width half maximum (FWHM) of each peak is deduced from the measured spectrum. For comparison, the spectrum of a high brightness blue-phosphorus LED is also measured.

B. *Measuring the parameters of an LED photodetector*

In this section, the experiments are devised to characterize the parameters of the LED as photodetector. These include the response linearity at each incident light colour, the effect of reverse bias on the responsivity of the LED photodetector and its 3-dB bandwidth, the angle of best reception as well as the FWHM of its acceptance cone.

The responsivity R of a photodetector is defined as the magnitude of the photocurrent I_p produced relative to the incident optical power P_o on the photosensitive area [14]:

$$R = \frac{I_p}{P_o} \tag{4}$$

The higher the responsivity of a photodetector the better the response. Higher responsivity values are achieved with greater reverse bias voltages and photo-detecting area. The responsivity is also dependent on the wavelength of the incident photons [14].

To measure the responsivity of the LED photodetector at different reverse biases and at different wavelengths, the experimental setup in Fig. 2 is proposed. On the transmitter side an RGB LED is connected in series with a 220 Ω resistor and driven by an adjustable power supply to vary the input current and hence the output optical power. The transmitter sub-LEDs are lit one at a time. The receiver RGB LED is placed at d = 3 cm away from the emitter, directly facing the transmitted light. The sub-LEDs are reverse biased and connected to a 1 MΩ resistor. The voltage drop across the resistor is measured using a multi-meter at different reverse bias voltages (0, 2, 5 and 25 V). The measured voltage drop is directly related to the produced photocurrent of each sub-LED by Ohm's law. The responsivity is then calculated by dividing the produced photocurrent by the received optical power. The aim of this experiment is to find out the most suitable emitter sub-LED and detector sub-LED combination for the LED-to-LED link.

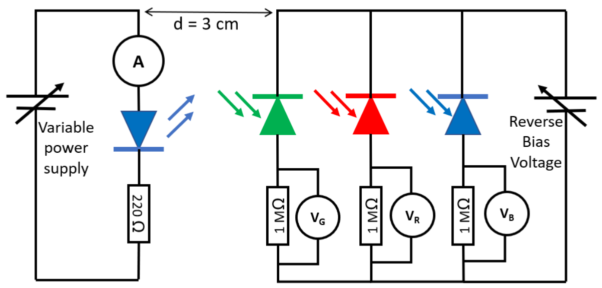

Fig. 2 Experimental setup for measuring the responsivity of RGB LED photodetectors at different reverse biases and wavelengths

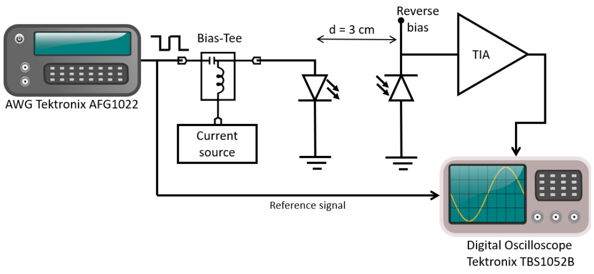

Fig. 4 Experimental setup for testing the bandwidth of an RGB LED photodetector at different reverse biases

To measure the bandwidth of the LED photodetector at different biases, the experimental setup in Fig. 3 is proposed. The emitter blue phosphorus high brightness LED is driven by a bias-Tee configuration that provides a DC current and an AC voltage from an arbitrary waveform generator (Tektronix AFG1022). The AC signal consists of a 100 kHz square wave of duty cycle 50% and 5 Vpp amplitude. At d = 3 cm from the emitter LED the RGB LED photodetector is placed coaxially and in direct line of sight. The output of the LED photodetector is amplified by a transimpedance amplifier (TIA) then displayed on the oscilloscope and stored for offline processing. As reference signal, the AC signal from the AWG is displayed simultaneously with the output signal.

By measuring the rise time t_r of the LED photodetector output signal, the bandwidth BW_{3dB} of the LED photodetector can be determined as follows:

$$BW_{3dB} = \frac{0.35}{t_r} \tag{5}$$

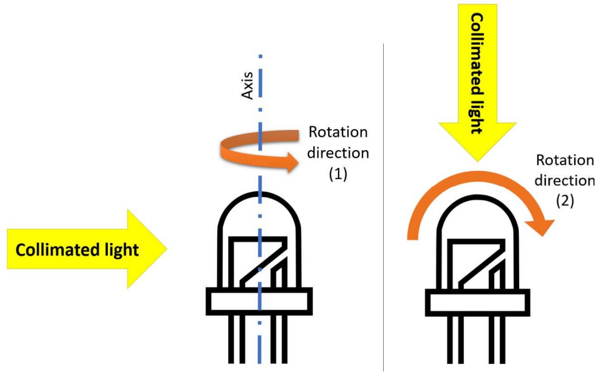

Fig. 3 Rotation directions for measuring the best reception angle

The rise time is defined as the time it takes the output potential to rise from 10% to 90% of the potential difference between the low (V_{OL}) and high (V_{OH}) voltage levels.

The measurements for the rise time of the photodetector were repeated for red and green sub-LEDs as well as for a PIN photodiode at no bias and at 25 V reverse bias. The measurements are repeated when the receiving sub-LED photodetectors are forward biased with 2 V. The blue LED is omitted from the measurements as detector due to its low responsivity to both the red and the green light, as proven by the previous experiments.

The last experiment aims to measure the response of the LED photodetector at different angles of the received light. A small motor is programmed to rotate the attached 2 V reverse biased red and green sub-LEDs of an RGB LED in 2-degree intervals in front of a blue-phosphorus light source around and perpendicular to its own axis respectively. The rotation directions are shown in Fig. 4. A convex lens is placed between transmitter and receiver at the appropriate focal length to create collimated light. This guarantees that the sub-LEDs receive the same light intensity at all rotation positions. The output current is amplified and measured by a current meter. For comparison, the response of a PIN photodiode is measured as well.

IV. RESULTS AND DISCUSSION

A. *LED transmitter*

Measuring the sub-LEDs output power gives an indication for the sub-LED which is best suited as a transmitter for an LED-to-LED communication system. Besides, the peak wavelengths of the three colors gives insight of the energy of emitted photons and hence the suitable sub-LED for detecting those photons. When testing the output optical power of an RGB LED relative to the input current, the measurements prove that at each supply current the blue sub-LED provides the highest optical power, followed by the green then the red sub-LED. The graph in Fig. 5 summarizes the results of the measurements. It shows that the transmitted optical power is proportional to the current supplying the sub-LEDs. This highly linear relationship between the input current and output optical power is advantageous in the case of intensity modulation. At 20 mA the blue sub-LED provides nearly 0.8 mW of optical power at 3 cm distance, while the green sub-LED and the red sub-LED could only provide 0.45 mW and 0.17 mW respectively.

Further investigations of the RGB LED spectrum confirm those results. The output of the spectrum analyser both for the blue phosphorus LED (dotted line) and the RGB LED (solid line) is shown in Fig. 6. The light intensity is normalized to the maximum level of the white LED. The spectrum of the RGB LED consists of 3 peaks with maximum at 465.27 nm (blue), 515.66 nm (green) and 629.77 nm (red). The peak heights confirm the results of the previous experiment. The FWHM of the three sub-LEDs are 19.34 nm, 30.09 nm and 15.77 nm for blue, green and red respectively, which is narrower than that of the white LED peak. The energy of the photons emitted by each sub-LED can be calculated from the peak wavelengths according to equation (2).

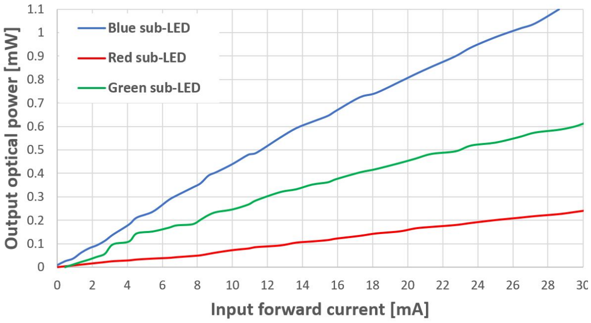

Fig. 5 Linearity of optical power relative to the current of an RGB LED

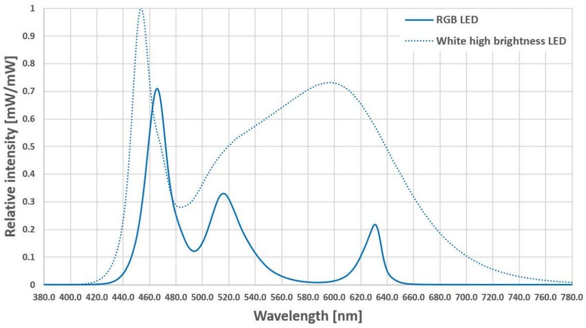

Fig. 6 Spectrum of an RGB LED and a blue-phosphorus LED

The photon energies emitted by the red, green and blue sub-LED at peak wavelengths respectively are 1.969 eV, 2.404 eV and 2.665 eV. That means that theoretically, the blue light should be easily detected by the green and red sub-LEDs respectively, because its photons have a higher energy than the energy gaps of those sub-LEDs. Similarly, the green light can be detected by the red LED. However, the red light cannot be detected by either of the sub-LEDs due to its low energy, besides being of the lowest power. This makes the red sub-LED the worst choice for transmitter and proves that the blue and green sub-LEDs have higher potential as transmitters.

B. *LED Photodetector*

Fig. 7 shows the response of the red, green and blue sub-LEDs at no bias when they receive continuous wave light from the blue sub-LED (solid line) and from the green sub-LED (dotted line). According to equation (4), the responsivity is the change of the photocurrent relative to the change of incident optical power and can hence be displayed as the slope of the curve shown in Fig. 7. Since the graphs for all three sub-LEDs show a nearly constant slope and linear response to the rising optical power, it can be deduced that the responsivity of the LED photodetectors stays constant over the range of optical light power between 0.1 and 1 mW. Moreover, by comparing the slopes of the sub-LEDs responses to the incident light, the red sub-LED has the highest responsivity when receiving green light while the green sub-LED is better equipped to receive blue light. The blue sub-LED shows the worst responsivity when exposed to blue light and is non-responsive to green light. None of the three sub-LEDs were able to respond to incident red light. Even when the transmitter red sub-LED is replaced by a LASER diode of the same wavelength but much higher optical power, all three sub LEDs produced no photocurrent in response. Hence those results were omitted from this figure.

In conclusion, a green sub-LED as source and a red sub-LED as detector are the best combination for an LED-to-LED communication link. In terms of responsivity, this combination is directly followed by a blue sub-LED source

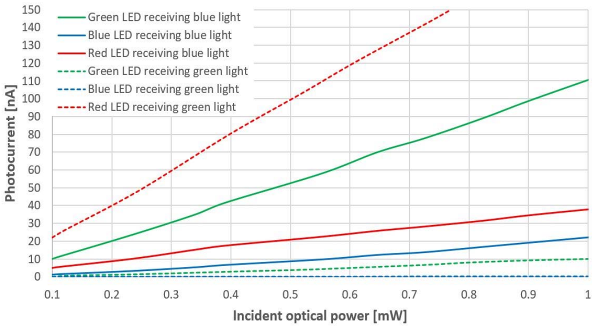

Fig. 7 Response of RGB sub-LEDs to green and blue light at no bias

and a green sub-LED detector. These two combinations have a good potential for WDM based LED-to-LED communication.

In order to measure the effect of reverse biasing the LED photodetector on its responsivity, the previous experiment is repeated with the sub-LEDs reversed biased at 2, 5 and 25 V (max. voltage before break-down of sub-LEDs). The average responsivity values of each sub-LED at each reverse bias voltage when exposed to green and blue light sources are summarised in Table I. While for the green LED the reverse bias does not majorly affect the responsivity, the red LED shows a relatively high increase in responsivity from 212.8 nA/mW to 256.3 nA/mW when its reverse bias rises from 5 V to 25 V. The responsivity stays almost constant however between 0 and 5 V reverse bias. Similarly, the red sub-LED responsivity to blue light rises from an average of 43 nA/mW to 67.5 nA/mW when the reverse bias increases from 0, 2 V or 5 V to 25 V. The blue sub-LED on the other hand still has the lowest responsivity of all three sub-LED photodetectors. It shows no response at all to green light even at the highest possible reverse bias voltage. When exposed to blue light, its already low responsivity drops even further from 17 nA/mW to 6 nA/mW when the reverse bias voltage increases from 0 V to 25 V. This is because its energy gap widens even more with reverse biasing, making the lower energy photons from the blue light not able to stimulate electrons into the higher energy state.

In conclusion, this experiment proves that only the red sub-LED photodetector positively responds to high reverse biasing of 25 V, while the blue and green sub-LEDs remain unaffected in terms of responsivity. It also demonstrates that the increase in responsivity of the red LED due to the increasing reverse bias in not linear. This means that while an increase from 0 V to 5 V reverse bias causes no improvement in responsivity, increasing the reverse bias from 5 V to 25 V results in a 20% increase in responsivity on average. This low dynamic range and marginal improvement with higher reverse bias makes RGB LED-to-LED communication a valid option for IoT devices.

TABLE I. RESPONSIVITY OF SUB-LEDS AT DIFFERENT REVERSE BIASES [NA/MW]

	Green transmitter			**Blue transmitter**		
detector / bias	**Red**	**Green**	**Blue**	**Red**	**Green**	**Blue**
0 V	202.4	8.25	N/A	42.35	105.4	17.3
2 V	212.8	10.8	N/A	43.6	108.4	14.3
5 V	212.9	7.07	N/A	42.6	107.6	9.45
25 V	256.3	11.55	N/A	67.5	117.2	6

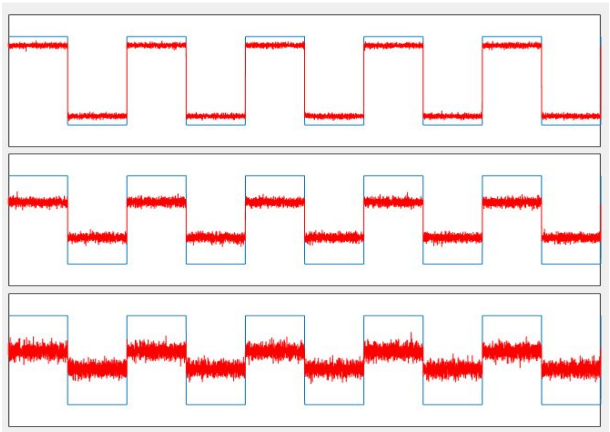

Fig. 8 Waveforms of the red sub-LED at 25 V reverse bias (top), no bias (middle) and 2 V forward bias (bottom) compared to the ref. signal (blue)

While the reverse bias has no effect on the responsivity of the green sub-LED, the next experiment proves that it has a major effect on its bandwidth as a photodetector. The measured rise times and the bandwidth of both the red and green sub-LED photodetectors as well as an off-the-shelf PIN photodiode are compared in Table II. The bandwidth of both the red and green sub-LEDs more than double when the reverse bias increases from 0 to 25 V. Moreover, the measurements prove that although the PIN photodetector has a larger bandwidth than the red and green LEDs at 25 V reverse bias, its bandwidth is mediocre compared to the LED photodetectors at no bias. Fig. 8 shows an example of the waveform received by the red sub-LED (red) at all three bias levels compared to the reference signal (blue).

In addition to being able to receive at acceptable bandwidths under no and reverse bias, the LED photodetectors can detect light signals with a small data rate when forward biased. The experiment is repeated with the LED photodetectors forward biased at 2 V and the results prove that the LEDs can sense incident light even when dimly lit. This is because at 2 V forward bias, the depletion region of the sub-LEDs is narrowed but has not yet entirely diminished, allowing thereby the weak detection of incoming photons. This feature makes the LED photodetector especially useful in applications requiring quick switching between transmitting and receiving modes and in light fidelity (Li-Fi), where the light is not allowed to be perceived as off by the human eye due to communication.

While the LED photodetector is inferior in terms of responsivity and bandwidth to a PIN photodiode at reverse bias, it is possible to achieve acceptable data rates (higher than 1 kbps) with the red and green LEDs as photodetectors at 0 V and low reverse biases.

TABLE II. BANDWIDTH OF PIN PHOTODIODE AND SUB-LEDS AT DIFFERENT BIAS VOLTAGES

Bias	**0**	**-25 V**	**+2 V**
Red	2.4 MHz	4.9 MHz	0.8 MHz
Green	2.4 MHz	6 MHz	3.2 MHz
PIN	0.1 MHz	9.2 MHz	N/A

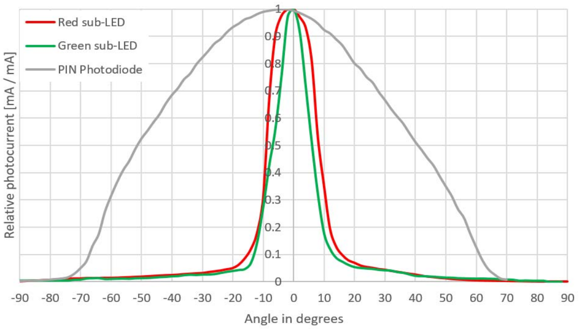

Fig. 9 Response of sub-LEDs and PIN photodiode at different angles

When testing the angle for best light reception, the measured output of the experiments indicates that the rotation of the LED around its own axis (Rotation direction (1)) does not affect its output. The measured output fluctuates around the same value irrelevant of the angle of incident light. When rotating the LED in a semi-circle perpendicular to the incoming beam of light however (Rotation direction (2)), the LED shows the highest response to incident light when it is coaxial with and directly facing the light source. Fig. 9 displays the response of the green and red sub-LEDs as well as a PIN photodiode. The field of view of the LED photodetector is calculated from the curves and found to be around 18 degrees for the red and 14 degrees for the green sub-LED, as opposed to around 90 degrees for the PIN photodetector. The LED photodetector is hence a directive photodetector which could find value in indoor localization applications.

V. CONCLUSION

In this paper the RGB LED is characterized as emitter and photodetector with the aim of utilizing it on both ends of an LED-to-LED visible light communication channel. The implemented experiments show that the RGB LED produces light with peak wavelengths at 465.27 nm (blue), 515.66 nm (green) and 629.77 nm (red) with the blue light having the highest optical power of all three. Moreover, its emitted light power is linearly proportional to the supplying current and can therefore be utilized for intensity-modulation based applications. As a photodetector, the responsivity of the RGB LED is tested at different reverse biases and wavelengths. These experiments prove that the red sub-LED has the highest responsivity when detecting green light followed by the green sub-LED detecting blue light. The blue sub-LED is the worst choice for photodetection since it has the largest energy gap of all three, preventing lower energy photons of the red and green light from producing any current. Being able to send and receive light with different sub-LEDs combinations offer a good potential for WDM and can therefore increase the overall bandwidth of the LED-to-LED system without increasing the number of photosensitive elements. The responsivity of the LED photodetector improves only slightly at a reverse bias of 25 V. This makes an LED photodetector a more energy efficient option than the PIN photodiode on the expense of having a lower sensitivity. The LED's 3-dB bandwidth increases to the double value when the reverse bias increases from 2 V to 25 V. It is also experimentally proven that – unlike the PIN photodiode - the LED can be utilized as a low sensitivity photodetector even when forward biased and dimly lit. Last, the LED photodetector has a narrow cone of acceptance of only 18 degrees as opposed to almost 90 degrees in the case of PIN photodiodes, which makes it a more directive receiver.

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