Prototyping Design of Low-Cost Bias-T Circuit Based-on Op-Amp for Visible Light Communication

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Abstract**—**The visible light communication (VLC) exploits the LED as an antenna in which only works on "forward bias" conditions. Therefore, when the VLC has an input signal with minus voltage it will be clipped, and only the positive side is transmitted by LED. If the VLC has an analog signal input with a completely positive amplitude, the LED may exhibit flicker-effect when the input frequency is relatively low to medium. Therefore, the correct method for LED conditioning is by lumping the information signal in the DC area. The "Bias Tee" (Bias-T) is a commercial module that is most commonly applied for LED conditioning with analog input signal characteristics. Although the performance is powerful and significant for transmitting the high-frequency, the cost is relatively inexpensive. Therefore, this study proposes a low-cost Bias-T module for a low bit-rate VLC system. Instead of the Bias-T generally, that uses an inductor and capacitor, this module is built by Op-Amps circuit which consists of 1) buffer Op-Amp as DC input ($V_{DC\text{-}OFFSET}$), 2) variable Pre-Amplifier as signal information input (V_{INF}), 3) summing amplifier to combine these two signals (V_{INF} + $V_{DC\text{-}OFFSET}$) and 4) current amplifier for increasing the high-power LED with no-flicker (stable illumination). The designed Bias-T is built on a discrete component. The evaluations involved three approaches, given the input signal: 1) with a single carrier in sine form, 2) analog signal from digital signal processing (DSP) board, 3) audio signal generated from a personal computer. In summary, the Bias-T works as properly as expected.

Index Terms**—**Bias-T, low-rate data transmission, operational amplifier configuration, visible light communications

I. Introduction

Visible light communication known as VLC promises green communication technology in the future [1]–[3]. The VLC system is divided into three major parts: transmitter block, receiver block, and optical channel as visualized in Fig. 1. This figure depicts the experimental setup of the VLC system for high-speed applications. Furthermore, it includes a personal computer (PC) connected to a digital signal processing (DSP) module or pattern generator/arbitrary waveform generator (AWG), a low-noise amplifier (LNA) module, Bias-T module as an analog modulator of light-emitting diode (LED), a single LED or array LEDs. The receiver side is constructed by a photodetector amplifier (PDA) module in which it receives an optical power that is linear with the LED illumination level: The higher the LED luminance level the higher the photo-detector power received and vice versa [4]. Generally, a PDA module comprises a PIN/APD, a trans-impedance amplifier (TIA), and a fixed amplifier, and these three parts are integrated into a single product. In addition, the PDA output has 50 Ω of load resistance. Therefore, it is not required to match the circuit impedance after PDA. When the commercially available components were utilized as a detector system in the VLC system, the used photodetector must be integrated (e.g., PIN, APD, image sensor, and other types), with a TIA circuit [5] and amplifier with careful calculations.

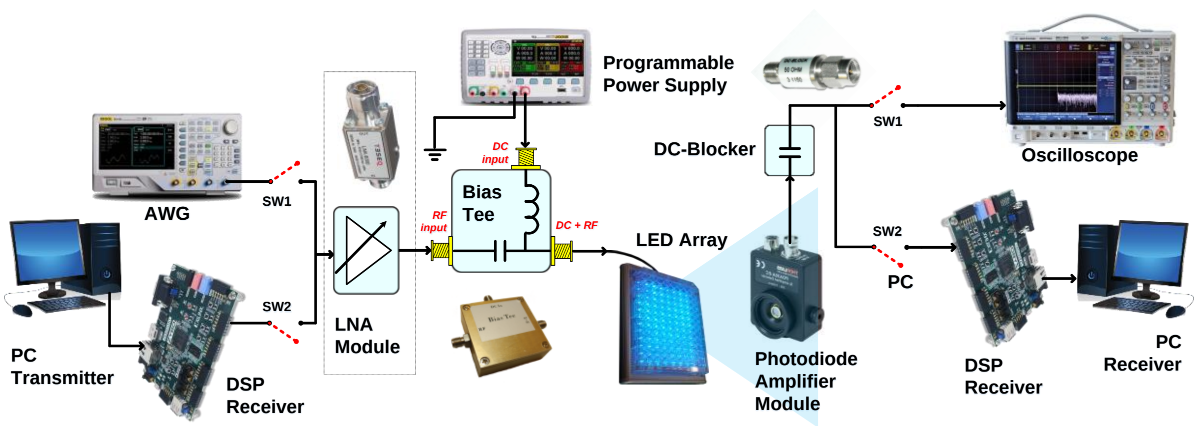

Fig. 1. Generic architecture of the high-speed VLC system utilizing commercial modules

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Furthermore, the photodetector not only generates the photocurrent (I_{PD}) sourced from the LEDs illumination but is also influenced by other lights in the indoor environment (known as ambient light noise). These include sunlight, background light, DC lamps such as a flashlight or other LED, incandescent, or fluorescent light with DC signal characteristics [6]–[9]. This DC component must be eliminated using the DC-offset remover through which the DC-blocker module can be utilized. The next stage is the amplifier module as the additional gain and its output is connected to the DSP receiver and PC to analyze bit-error-rate (BER) or digital oscilloscope. This helps to determine the signal-to-noise ratio (SNR) value, desired electrical bandwidth, and jitter characteristics via eye diagram. To obtain the constant received signal, the automatic gain controller (AGC) circuit on the receiver part [10], [11] can be utilized, while the Fresnel and convex lens are used for focusing the LED intensity in the optical channel.

As a form of wireless communication, the fundamental principle of the VLC system is that the received data must be equal to the transmitted data. Therefore, the LED driver is one of the main parts that act as a substantial part to mitigate the proper LED light from the flicker effect and the clipped signal (distortion) due to the linearity characteristic of the LED. In the transmitter side of Fig. 1, the commercial Bias-T module functions as a linear LED driver. This module is mostly implemented for Radio Frequency (RF) communication systems. Recently, this module has been widely exercised for VLC systems. It is called a "Tee" because the circuit base consists of three ports arranged in a "T" shape. Bias-T has one input for the RF channel, one input for the DC channel, and one output. The advantage of this module is that it offers the light-weight implementation (directly applied without major setting), powerful, and available in the market with varying bandwidths, from hundreds to thousands of Hertz (Hz). However, the price of a piece of the Bias-T module is relatively sumptuous [12]–[15]. This factor becomes a drawback when VLC is applied massively in closed commercial buildings (especially in the indoor area) or when the VLC functions for a low-rate data transmission motive.

Previous research states that the VLC enables all of the lighting devices (i.e., LED) to have dual functions: illumination device as well as information transmission purpose. This involves either high data or low data rates in the public/private/specific spot, certainly at reachable prices for installation. Therefore, a solution is required to redesign an optical system using low-cost commercial components that are readily found in the market [16], such as photodetectors, operational amplifiers (Op-Amps) as analog signal processing, or available DSP module [17], with appropriate on-chip system design [18], [19].

In transmitter section, the device that represents the role of the Bias-T has to be affordable, with low-complexity and good performance. Based on this brief explanation, the research and development of LED drivers are feasible. Therefore, this research introduces a new topology of Bias-T composed of Op-Amp circuits. With the same working principle, the benefit of this design compared to the commercial Bias-T module is an extremely lower cost. Moreover, the designed Bias-T is capable of applications for >5 Watt of LED power.

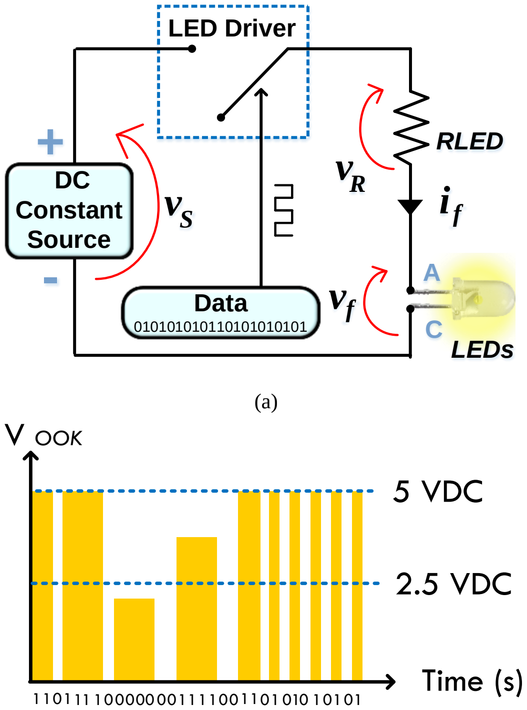
The LED driver uses a transistor configuration for optical wireless communication (OWC). Furthermore, VLC can be divided into two types, namely a switch with the best performance only while set to "cut-off" or "saturate" condition, or vice versa [20], [21]. For digital modulation such as on-off-keying (OOK), pulse position modulation (PPM), and pulse width modulation (PWM), it is recommended to use switch LED driver because these modulations represent two conditions of LED light, i.e., "off" or "on" condition (it means '0' or '1' logic). On the receiver side, the peak level of amplitude does not affect the data. However, it is worthy of note that it is not more or less than the tolerance limit of crisp logic: high (5/3.3/2.5 V_{DC}) or low (0 V_{DC}).

Fig. 2(a) shows the primary circuit of the switch LED driver and its circumstances when programmed with TTL logic: '1' or '0' as illustrated in Fig. 2(b). The second type is the linear LED driver which is the main topic of this research because it is one of the solutions to significant issues in the VLC system. An example is the nonlinear problem of the LED when the system utilizes an analog signal form, e.g., original audio-video signal (without encoding scheme) or modulated signal with orthogonal frequency-division multiplexing (OFDM) techniques [22].

Below is the list of prospective contributions from this research:

1) The circuit includes manual tuning to adjust the stable lighting due to the flickering effect. Through this proposed module, the LED will have dual functions: lighting as well as simplex communication.
2) Unlike previous work [23], this circuit can eliminate input signals containing DC offset through manual setting before being set into a linear region of LED.
3) Simple design with specific topology based on commercially available Op. Amp, including easy hardware implementation. Using a little number of electronic components, it can be realized in a small PCB package.
4) This Bias-T replacement circuit is easy to use (user-friendly).
5) Unlike the commercial, expensive Bias-T module, this design serves a low cost and retains the same performance and quality.
6) It can be used to transmit data using different LED colors (e.g., Red, Green, Blue, Yellow, etc.). The linear region of these different LED colors can be adjusted easily.
7) Unlike previous work [13], [24], this design can be used for different LED powers, ranging from 3 W to 15 W (due to the supply voltage limitation of Op. Amp component).
8) It enables the transmission of an OFDM signal with a low-speed digital clock.

The rest of this research is organized as follows: The first chapter discusses the proposed Bias-T for low-rate data transmission that consists of overview technology. The second chapter discusses the specifications of LED and Op-Amp, and the digital-to-analog (DAC) performance test and set-up of proposed Bias-T with several scenarios. Furthermore, the third chapter ascertains the results and analyses. The conclusions are drawn in the fourth chapter, and the end chapter is closed by acknowledgement, appendix and references.



(a)

(b)

Fig. 2. Switch LED driver: (a) the basic electronic circuitry of VLC system that uses digital modulation with constant amplitude, in this case is OOK signal. This illustration is reproduced from [25]; (b) brightness control on the LED light uses ARDUINO board as DSP module when 5 V_{DC} as reference voltage for logic high in which an amplitude above 2.5 V_{DC} is considered as logic “1” and under 2.5 V_{DC} is considered as logic “0”, reproduced from [26]

II. Bias-T Design

A. *Overview of Proposed Bias-T*

In the VLC system, the analog signal-based modulation technique is limited by the DC area which is the saturation condition of the LED, therefore it must be positioned around the DC area. The Bias-T module can be exploited as an analog modulator to position it on the appropriate DC area or even on the linear region of LED with precision.

From Fig. 1, it was observed that the Tee Bias module consists of passive components: capacitor (*C*) and inductor (*L*) [27]. The capacitor acts as a DC blocker, and prevents the DC signal from the power supply from reaching the DSP module. Meanwhile, the inductor functions in blocking the RF signal and passing the DC signal. The output of Bias-T is therefore a mixed-signal between the DC (V_{DC}) and RF (V_{INF}) signals.

Unlike the commercial Bias-T module which utilizes *L* and *C* components, the developed Bias-T in this research was based on general Op Amps. The working principle was the same: to mix the DC and RF signals.

Fig. 3 depicts the proposed bias-T that consists of four stages: 1) buffer circuit to hold the V_{DC} as well as voltage reference; 2) to hold the V_{INF}; 3) summing amplifier as DC-offset adder; and the last stage is current amplifier configured as an emitter buffer. To obtain the value of R_1, R_2, R_3, R_4 and R_{V2}, Eq.1, is used, while V_4 can be solved using Eq. 2. The result of non-inverting is shown in Eq. 3.

$$V_{\mathrm{LED}} = V_4 \tag{1}$$

$$V_4 = \left(\frac{\mathrm{R2}}{\mathrm{R2+R3}}\mathrm{Vin}+\frac{\mathrm{R3}}{\mathrm{R2+R3}}\mathrm{Vref}\right) * \left(1+\frac{\mathrm{R5}}{\mathrm{R4}}\right) \tag{2}$$

$$V_1 = \left(\frac{\mathrm{RV3}}{\mathrm{R1}}\right) *\mathrm{Vin} \tag{3}$$

To clarify equations (2) to (3), an example of the proposed linear LED driver setting will be provided. This design can be used for all types of LED and VLC applications with low-rate specifications, such as real-time long-distance voice communications [28], [29], audio transfer in the free space area [24], [24], image transmission [30], [31], low to medium quality of video stream [32], [33], low to a medium speed of real-time internet access [3], [34], etc. For example, the LED used as a transmitter in a VLC system has a linear range of 1 V_{DC}. However, it is important to note that in using the LED driver, it should be characterized by observing the I-V graph, to determine the working point and linear region.
The gain setting on the pre-amp variable block was 0.5 – 2 times the gain. For example, the input signal (V_{in}) from the DAC module was 1 V_{DC} (with peak-to-peak at +0.5 to –0.5 V_{DC}) going to the LED driver circuit. The range was already included in the LED linear region, which is 1 V_{DC}. Therefore, it is necessary to set Gain = 1x on the pre-amp variable block. This adjustment is made via the potentiometer RV_3 on the variable pre-amp block, which adjusts the output voltage of the DAC module. For example, the V_{out} of the DAC module that enters the LED driver is 0.5 V_{DC}, then the Gain setting = 2x. Meanwhile, if V_{in} = 2 V_{DC}, it has to be attenuated by 0.5 times to match the maximum voltage range in the LED linear region. In this circuit, the values of R_1, R_2, and R_3 are selected to be 1000Ω. The transfer function in equation (2) will then become equation (4).

$$V_4 = (0.5 * Vin + 0.5 * Vref) * \left(1+\frac{1\,k\Omega}{R4}\right) \tag{4}$$

The reference voltage (V_{ref}) is the output voltage of the variable resistor (R_{V2}) in the block buffer, therefore it can be written $V_{ref} = V_2$.

The voltage V_4 is the same as the voltage V_3, therefore it is written as V_4. Equation (4) shows that the input signal from the DAC module has been amplified half times, or alternatively, as derived from equation (3), where V_1 =

0.5*V_{in}. Consequently, the input signal is automatically weakened 0.5 times (measured by the pre-amp variable block output voltage) and needs to be amplified twice to keep the information signal at the linear voltage of the LED, which is 1 V_{DC}. The output voltage of the buffer block also gets half times the gain obtained from the equation = 0.5*Vref). Based on these conditions, the value of the resistor R_4 is calculated as follows:

$$\left(1+\frac{R5}{R4}\right) = 2 \text{ times}$$

Therefore R5 = 1 kΩ and R4 will be 1 kΩ

The value of R_4 should be 1000 kΩ, therefore the amplification of the information signal is equal to 2 times. The signal that has been amplified in the Summing amplifier block (output V_3) is then fed to the last block, namely the voltage follower transistor which is connected directly to the LED. The output voltage of the LED follows the input voltage of the Summing amplifier circuit (equation 1) because V_3 = V_4. The details of the explanation for V_{in} = 1 V_{DC} are explained in equations (5) and (6).

$$V_{LED} = (0.5 * Vin + 0.5 * Vref) * (2) \tag{5}$$

$$V_{LED} = (1 * Vin + 1 * Vref) \tag{6}$$

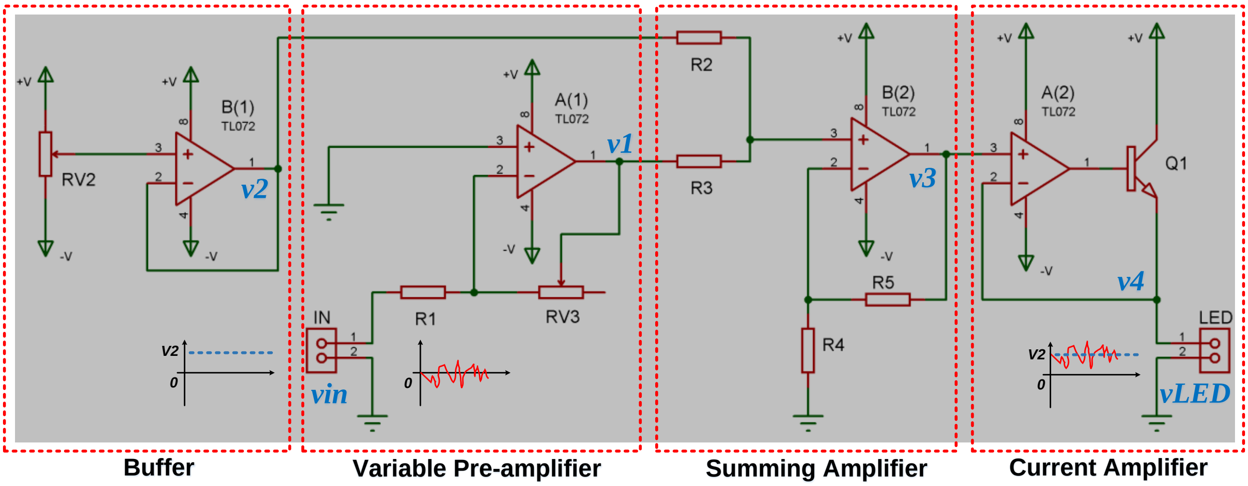


Fig. 3. The proposed Bias-T network/Linear LED driver circuitry

B. LED Specification

In this research, yellow-colored LED 12 V_{DC} (8 Watt) CREE XT-E model was used with yellow light as shown below. This LED has 120° of beam angle, 1 MHz of optical bandwidth, 585nm – 590 nm of wavelength and 1 V_{DC} of linear range, supplied by 11 to 12 V_{DC} [26]. (See Fig. 4)

Fig. 4. A photograph of physical form of yellow XT-E model, CREE LED with its light colour

C. Op-Amp Specification

General purpose Op-Amp with the model of TL072 from Texas Instrument, Inc. was employed in this research. This IC has a unique feature: low-noise JFET-Input Op-Amp and gain-bandwidth product up to 3 MHz with an effective bandwidth of about 1 MHz. Therefore, this IC is quite feasible for at least 500 kHz of bandwidth budget in low-rate data transmission. Another reason is that it is available in the local electronic market and is relatively cheap.

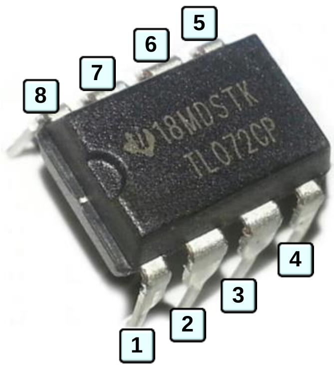


Fig. 5. A photograph of physical form of TL072 that has four pins (1 = Output A, 2 = Inverting A, 3 = Non-inverting A, 4 = V_{EE}, 5 = Non-inverting B, 6 = Inverting B, 7 = Output, and 8 = V_{CC})

The physical form of IC TL072CP is shown in Fig. 5. This IC is capable of working within the ± 20 V_{DC} voltage range. This agrees with the specified design that the Bias-T must successfully use up to 12 VDC for supplying high-power LED. From Fig. 3, the circuit only requires four Op-Amps: A(1), (A2), B(1) and B(2). Since the TL072 has two channels, the low-cost Bias-T hardware can be realized by two IC TL072.

D. DAC Performance

In this research, the standardized architecture from Fig. 1 was adopted for the SW2 scheme. The 10-bit DAC THS5651EVM board was also used for a linear LED driver input. The DAC module worked with an analog supply of 4.5 to 5.5 V_{DC} and 100 MSPS sample-rate [17]. Furthermore, the digital input was produced from a system-on-chip (SoC) board that employs FPGA Zybo. The frequency of the sinusoidal signal of DAC can be adjusted by tuning the frequency sampling of DAC and clock frequency of the register-transfer level (RTL) module.

Table I shows the data clock and DAC sampling clock configuration and its relationship with the output signal frequency from high to low. For the proof-of-concept (POC) the proposed Bias-T functionality, only output signal frequencies of 125 kHz were used. Therefore, the data clock was set 6.25 MHz with 3.125 MHz of clock sampling.

TABLE I: THE CONFIGURATION OF THE DATA CLOCK AND DAC CLOCK SAMPLING FOR THE RESULTING ANALOG SIGNAL AT VARYING FREQUENCIES

No	Data Clock	DAC Clock Sampling	Sine Signal Frequency
1	50 MHz	25 MHz	1 MHz
2	25 MHz	12.5 MHz	500 kHz
3	12.5 MHz	6.25 MHz	250 kHz
4	6.25 MHz	3.125 MHz	125 kHz
5	3.125 MHz	1.5 MHz	62.5 kHz
6	1.5 MHz	750 kHz	31.25 kHz
7	750 kHz	375 kHz	15 kHz
8	375 kHz	187.5 kHz	7.5 kHz
9	187.5 kHz	93.5 kHz	3.75 kHz
10	93.5 kHz	46.75 kHz	1.8 kHz

E. Testing Scenario

To ensure that the proposed Bias-T (Fig. 3) is applicable for a low-rate data transmission system based on VLC, it was evaluated in three ways as shown in Fig. 6. There were three switches (SW) used, namely SW1 as 1st switch, SW2 as 2nd switch, and SW3 as 3rd switch).

The various forms of the analog signal were generated as input signals: a sinusoid signal comes from a signal generator, OFDM signal from DSP board, followed by an audio signal. The tests were performed to prove whether the received signal of the analog front-end (AFE) circuit was similar to the transmitted signal. In this test, the photodiode used was the KONDENSHI SP-8ML, while the employed AFE circuit was composed of TIA, Pre-Amp, and analog filters [35].

As shown in Fig. 6, SW1 denotes the push button for the 1st scenario in which the proposed Bias-T receives a single carrier signal in sine form by the signal generator (GW INSTEK GFG-8210). 125 kHz of output frequency was set to be processed by the Bias-T circuit. The LED transmits the sine signal wirelessly via visible light. Afterwards, the photodiode will receive light intensity, which generates the small I_{PD} and further converts it to the voltage domain by TIA. The amplifier will then amplify the weak signal while the gained signal is inputted to the analog filter. Furthermore, the input of Bias-T and output of the last stage AFE circuit are probed by a digital oscilloscope to compare whether the received signal is still in sinusoid form and significant phase shifts did not occur.

To determine the Bias-T performances based on digital processing, the SW2 should be pushed, while SW1-SW3 must be opened. Firstly, the "data set" is generated by the PC-transmitter with SoC intermediaries embedded in the FPGA board. These transform the input signal to the modulated signal using an OFDM technique. The encoded data is then converted into an analog signal through the DAC module in parallel communication for processing by the proposed Bias-T.

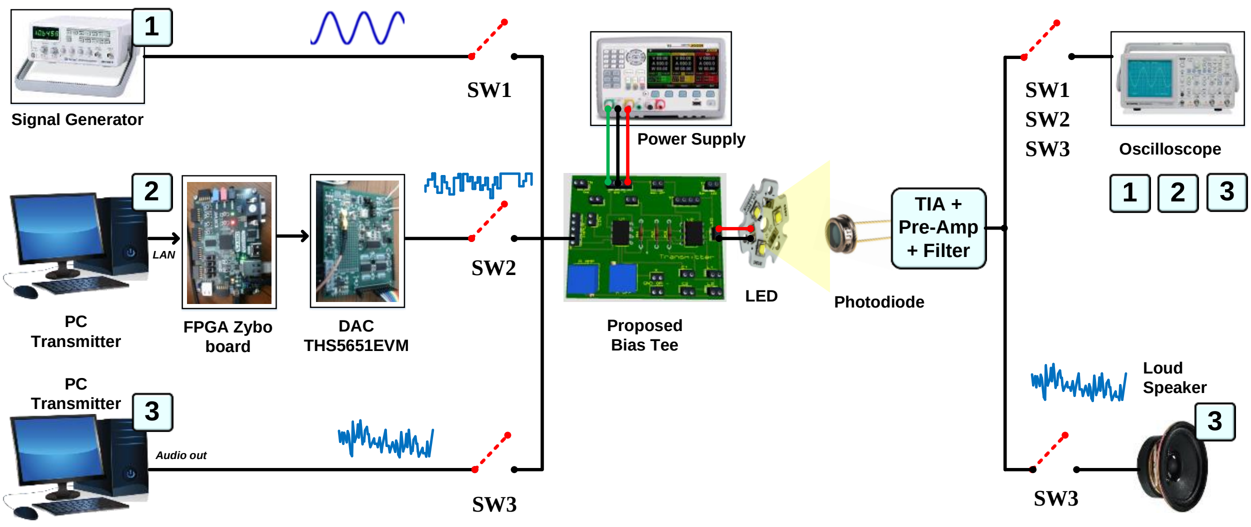


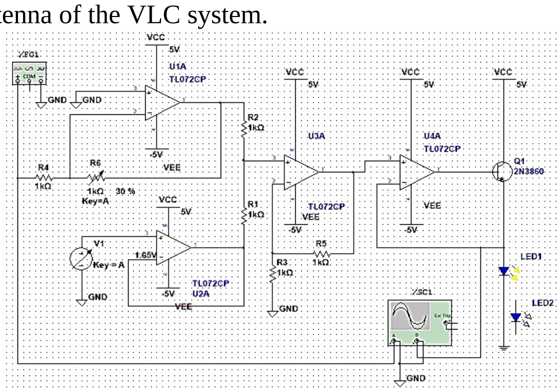
Fig. 6. POC of the proposed Bias-T, the switch SW1, SW2, and SW3 for choosing the test configuration

In the receiver section of the test set-up, the SW3 and SW1 must be pushed. In the 3rd scenario, the proposed Bias-T was tested to stream audio signals in real-time using intensity modulation direct detection (IM/DD). This testing method involves playing a piece of music on the PC transmitter, which is heard by the 8Ω loudspeaker. The physical wire is then replaced/ bypassed through an optical channel (visible light). Therefore, if the photodiode or LED is blocked by solid objects such as hands, walls, etc., the audio will not be properly heard. In this research, the BER analysis to compare transmitted audio signal against loudspeaker output was not used, therefore the test is only limited to quality observations on the oscilloscope of both signals. Furthermore, there are no clipped signals and the music can be played properly

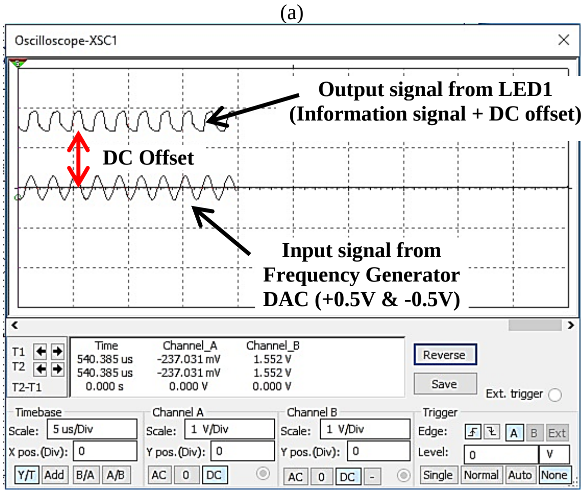
III. Results and Analysis

A. Performance of the Proposed Circuit under the Simulation

To ensure the success of the design, a simulation was carried out. The NI MULTISIM 14.0 student version software was used to determine the functionality of the LED driver design, whether the input signal from the DAC module was successfully added to the DC signal. Henceforth, this output signal was transmitted by the LED into the IM/DD domain. The input in the simulation utilized a virtual frequency generator which generated a sine signal of 0.5 Vpp. This device represents the functionality of the DAC module. Furthermore, the output and input voltages were observed on the virtual oscilloscope. The simulation circuit is shown in Fig. 7(a) which refers to the circuit in Fig. 3, where LED1 is the antenna of the VLC system.



(a)



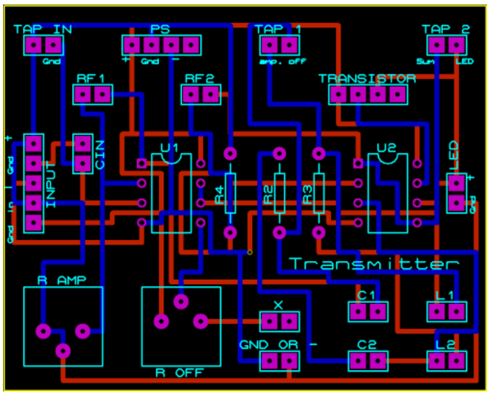
(b)

Fig. 7. LED driver simulation: (a) circuit simulation; (b) signal capture on a virtual oscilloscope on MULTISIM V.14 comparing the input signal with the LED anode (Simulation settings are single carrier signal = sinusoid, amplitude = 0.5 Vpp, input frequency = 500 kHz)

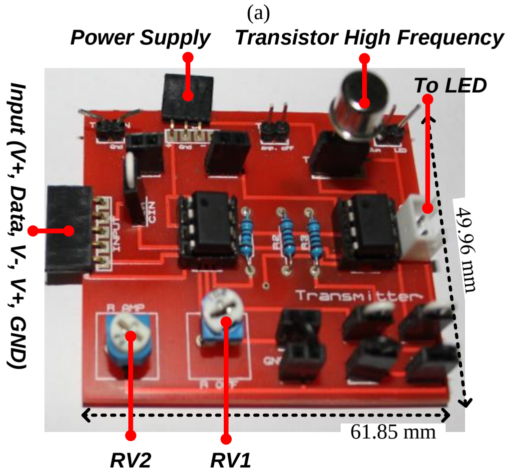
The simulation results in Fig. 7(b) showed that the LED can light up (indicated by yellow on LED1) while carrying a sinusoidal signal. The variable resistor settings and resistor components are in accordance with the calculation. If the Gain is too large, the signal will be cut off and the LED will flash. Additionally, if the DC offset voltage is too high, the signal will be cut off. If the DC offset voltage is too low, the LED (LED1) will not light up. This condition is therefore the same as LED2 (not lit).

B. Hardware Implementation

After the circuit was functionally verified on the simulation medium, it was then implemented as the circuit in Fig. 3. Fig. 8(b) visualizes the implemented Bias-T using discrete components based on Op-Amp referred to the circuit in Fig 3.



(a)



(b)

Fig. 8. Hardware prototype of proposed Bias-T

There are two potentiometers as the tuner of DC offset and amplifier gain, three channels of the power input (V_{CC}, ground, and V_{EE}), five channels of the input signal (V_{CC}, ground, V_{EE}, data, and ground), and one output for a single LED pin. Furthermore, Fig. 8(a) shows the layout of a double-layer printed circuit board on Proteus 7.0 Student version software.

C. Functional Test

The experimental setup is shown in Fig. 9, consisting of a PC to play the music, programmable power supply, proposed Bias-T, Digital Oscilloscope, jack audio output, analog front-end receiver, and loudspeaker. Fig. 10(a) to (c) are the captured image of the test results from each scenario, e.g., input signal generated by function generator, multilevel signal produced from DAC module, and audio signal sourced from an audio output of the PC, respectively. There were two signals on the digital oscilloscope. The top signal was the LED output, where the analog signal can be inserted in DC area. This signifies that LED not only lights up (turn on) but also transmits the information signal in different forms with low-frequency. The bottom one is the output signal from an analog filter.

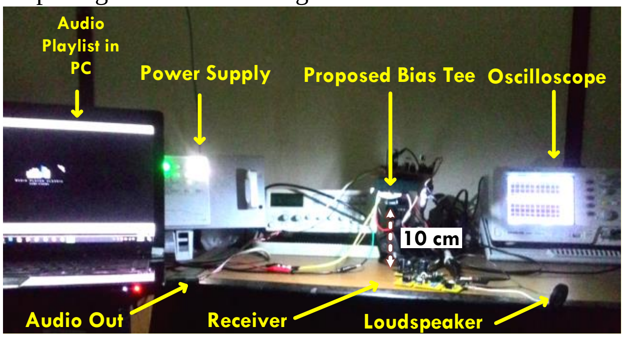
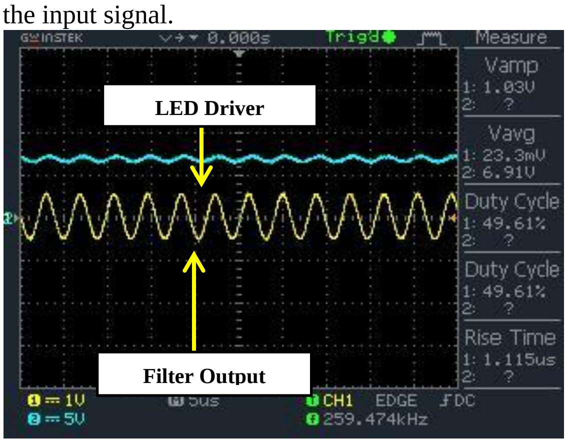
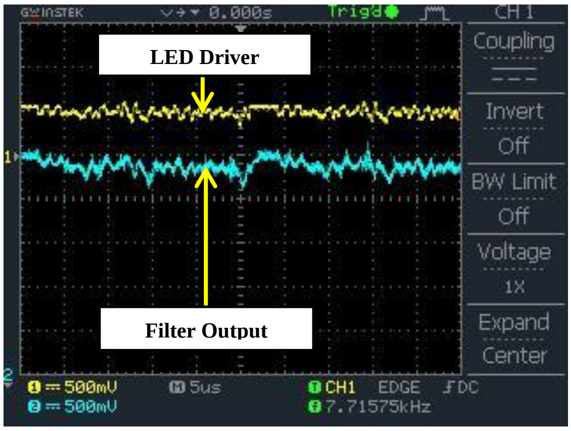


Fig. 9. A photograph of performance test of the proposed Bias-T for 3rd scenario. The room condition is 0 lux.

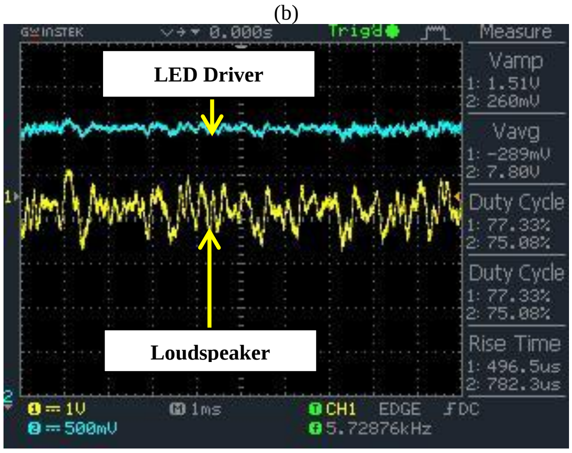
From the observation of both signals, top *vs* bottom, they are relatively the same. Therefore, the functional work of the Bias-T that uses Op-Amp can be highly recommended to represent the usability of the commercial Bias-T module in the VLC system, particularly for low-speed. The results of functional testing in the laboratory, as in Fig. 10, confirmed the success of the simulated media (Fig. 7). The linear LED driver designed in this research functioned like a Bias-T module, namely $V_{LED} = V_{information} + V_{DC}$, where $V_{information}$ is a signal that comes from the digital signal processing section [36]. In this case, it is called a DAC module. The VDC is the DC offset voltage to position the information signal in the linear region of the LED. The bandwidth of the LED driver has also been measured using a standard procedure, and a cut-off frequency of around 400 kHz was obtained. The details are elaborated in [26]. Table II shows the comparison between this LED driver and other studies in terms of three aspects: effective bandwidth, LED power, and adjustable DC offset of the input signal.



(a)



(b)



(c)

Fig 10. Captured signal from the digital oscilloscope: (a) 1st scenario; (2) 2nd scenario; and (3) 3rd scenario

TABLE II: COMPARISON BETWEEN PROPOSED LED DRIVER WITH OTHER WORKS IN TERMS OF FUNCTIONAL ASPECTS

References	LED power	Cut-off frequency	Adjustable DC offset
Mirvakili, et al. [37]	N.A.	5000 kHz	No
Fuada, et al. [13]	8 Watt	250 kHz	No
Sheu, et al. [38]	0.05 Watt	N.A.	No
Fuada, et al. [24]	3 Watt	300 kHz	No
Adiono, et al. [23]	9 Watt	150 kHz	No
Kruse, et al. [39]	18 Watt	1300 kHz	No
This work (Self-design)	3 – 15 Watt	400 kHz	Yes

D. Cost Analysis

This section compares the proposed circuit with the commercially available Bias-T module that has been widely used to demonstrate the VLC system. As stated in the research objectives, these series of LED drivers are built with affordable components which in total (including PCB manufacturing process) cost < 10 USD. Meanwhile, the Bias-T module has a price above 100 USD, excluding shipping costs to Indonesia. This price value can be seen on the manufacturer's website or the official marketplace. Furthermore, other problems occur in the process of Bias-T delivery, where some manufacturers require a minimum quantity that should be ordered (only one Bias-T module cannot be purchased). Table III is a comparison of the prices of several Bias-T modules that have been used in previous studies and their frequency ranges. Although there are significant differences in operating frequency, the similarity is found in the functionality; this linear LED driver is the same as the Bias-T module. The proposed circuit has been successfully tested in real applications, e.g., Li-Fi [34] and audio transmission system [40].

VLC is a system that offers joint illumination and communication. There are three essential issues in developing a VLC system as defined by [41], i.e., efficiency, communication speed, and cost factors. To obtain the low-cost target, a trade-off between these three major problems is required. This research has succeeded in offering low-cost aspects despite the efficiency and data transfer speed become the trade-off.

TABLE III: COMPARISON BETWEEN PROPOSED LED DRIVER WITH COMMERCIAL BIAS-T MODULE IN TERMS OF COST

Bias-T model	Used in	Range of operation frequency	Cost
ZFBT-6GW+	[46], [47]	100 kHz – 6 GHz	High
AEROFLEX 8210	[48], [49]	10 kHz – 12.4 GHz	High
ZFBT-4R2GW+	[50]	100 kHz – 4.2 GHz	High
JEBT-4R2GW	[51]	100 kHz – 4.2 GHz	High
ZX85-12G+	[52], [53]	200 kHz – 12 GHz	High
This work (Self-design)	[40], [54]	800 kHz	Low

For low-rate communication applications, the module replaces the role of the Bias-T module which also offers a more economical advantage, considering the very high price of Bias-T. Some of the applications of this circuit are in the hospital area, for example, the transfer of health data such as human temperature, ECG and EEG signals, etc. It is also used in an airplane cabin for wireless music streaming, in a shopping center for sending visible light-based discount notifications, voice and simple data communications in military sector [42], and many other applications. The LED driver in this research supports the real-time demonstration of VLC systems, is simple, practical, and simplifies the deployment process due to the affordability of production costs. Further development of the LED driver circuit is necessary, as it is one of the issues in prototyping commercial VLC systems [43], [44]. It is recommended to use off-the-shelf components to design an analog front-end containing the LED driver block to support low-cost VLC systems [45] and realize the consumer-based product of the VLC system. Therefore, this technology in tandem with IoT technology can penetrate the community more quickly, making it easier to use every day.

IV. CONCLUSION AND FUTURE WORKS

The implementation of OWC circuits and systems, specifically VLC, in major applications is challenged by the price factor. To accomplish the low-cost target, further studies are required for designing the low-complexity and inexpensive materials. In this study, the transmitter section of the VLC system was the point of focus. The Bias-T circuit developed in this research is composed of four Operational Amplifiers configurations: buffer, variable pre-amplifier, summing amplifier, and current amplifier. The developed Bias-T (linear LED driver) was tested using three scenarios: single-carrier signal as an input, and then OFDM signal and an original audio signal. The results showed that the working principle of the proposed circuit represents the commercially available Bias-T module functions: the 12 V_{DC} yellow LED transmits these signals efficiently without flickering or distortion (due to the clipping signal), while the AFE circuit can receive these signals properly. The proposed circuit was dedicated to low-rate data transmission via visible light that was targeted on short-range indoor communication.

CONFLICT OF INTEREST

The author declares no conflict of interest.

AUTHOR CONTRIBUTIONS

S.F. proposed the concept, designed, realized, carried out the demonstration, analyzed the data of functional tests, delineated all of the pictures in the manuscript, and contributed to the writing of the manuscript. The author approved the final version.

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