Bridging the Virtual and Hands-On Laboratories for Small-Signal Amplifier Circuits

Wahidah Abd Halim
Fakulti Teknologi dan Kejuruteraan Elektrik
Universiti Teknikal Malaysia Melaka
Melaka, Malaysia
wahidahhalim@utem.edu.my

Dinesh Subanthiran
Fakulti Teknologi dan Kejuruteraan Elektrik
Universiti Teknikal Malaysia Melaka
Melaka, Malaysia
dineshsubanthiran@gmail.com

Siti Azura Ahmad Tarusan
Fakulti Teknologi dan Kejuruteraan Elektrik
Universiti Teknikal Malaysia Melaka
Melaka, Malaysia
sitiazura@utem.edu.my

Auzani Jidin
Fakulti Teknologi dan Kejuruteraan Elektrik
Universiti Teknikal Malaysia Melaka
Melaka, Malaysia
auzani@utem.edu.my

Muhammad Zaim Mat Rosdi
Fakulti Teknologi dan Kejuruteraan Elektrik
Universiti Teknikal Malaysia Melaka
Melaka, Malaysia
muhdzaim1013@gmail.com

Muhammad Rabani Mohd Ali
Fakulti Teknologi dan Kejuruteraan Elektrik
Universiti Teknikal Malaysia Melaka
Melaka, Malaysia
mrabani685@gmail.com

***Abstract*— This paper presents an innovative approach to teach bipolar junction transistor (BJT) small-signal amplifier circuits in the laboratory, with a focus on simplifying the learning process for undergraduate students. In traditional Analog Electronics laboratory, students often face difficulties in constructing analog electronics circuits on breadboard, sometimes struggling even to begin the experiment. While BJT small-signal amplifiers may appear to be a basic analog electronics application, they remain one of the more challenging circuits for students to successfully assemble during lab sessions. To further enrich the educational experience, a multifaceted instructional approach is proposed. Tinkercad was utilized as an educational tool, effectively bridging the gap between theoretical concepts and practical application to enhance understanding of BJT small-signal amplifier configurations. Furthermore, EasyEDA was used to design a custom printed circuit board (PCB) for integration of BJT small-signal amplifier configurations onto an educational trainer board. These configurations comprised common-emitter, common-collector, and common-base amplifiers. This trainer board aims to streamline the hands-on experience, enrich students' knowledge and competencies, and reduce the learning time taken to understand the small-signal amplifier circuit concept.**

Keywords— virtual laboratory, hands-on laboratory, small-signal amplifiers, analog electronics

I. INTRODUCTION

In the past decade, many higher education institutions have decided to switch from the standard way of conducting experiments to new, more modern ways. Virtual or remote laboratories are often used for different purposes in these methods [1]. Along with the passing of time, virtual or remote laboratories are increasingly prevalent in higher education courses, especially during times like the COVID-19 pandemic [2-5]. The COVID-19 pandemic significantly transformed global educational practices, urging institutions to swiftly adjust to distance learning settings. This transition posed significant difficulties for engineering education since hands-on laboratory sessions are crucial for developing practical abilities and enhancing theoretical comprehension. The abrupt suspension of face-to-face activities required the investigation of alternate approaches to continue laboratory-based learning.

The virtual laboratory has evolved as a practical option, enabling students to simulate real-world Analog Electronics laboratory experiments at their residences safely and conveniently [1]. The increased utilization of virtual laboratories facilitates the reduction of laboratory space and redundant cost for equipment. Numerous circuit simulators, including EasyEDA, LTspice, Multisim, Proteus, and PSpice, are known as advanced tools for researchers and designers seeking to understand the way circuit design and schematics functionality. Tinkercad has demonstrated versatility and efficacy as a platform for online practical sessions in electronics, robotics, and related disciplines [2-8]. Tinkercad, originally created as a three-dimensional (3D) design tool, has broadened its functionalities to encompass virtual circuit simulation [9]. The platform is free to use and does not require installation; furthermore, it operates directly in web browsers, rendering it exceptionally accessible for students with constrained technical capabilities.

This research examines the application of Tinkercad as a virtual laboratory platform for simulating bipolar junction transistor (BJT) small-signal amplifier circuits. The main aim is to illustrate how Tinkercad, in addition to an educational trainer board, can significantly improve the teaching and learning of Analog Electronics laboratory course. It provides a simple, secure, and accessible platform for students to conduct virtual experiments prior to working with actual hardware, rendering it an essential tool for educators in introducing works related to analog electronics projects and experiments. The use of Tinkercad simulations enables students to acquire a comprehensive understanding of the principles governing BJT small-signal amplifiers, thereby equipping them for practical applications and experiments. Consequently, this approach decreases the time and troubleshooting required during hands-on laboratory sessions and reduces the overall study hours necessary for material familiarization.

This paper asserts that although simulations are advantageous, they should complement instead of replacing conventional laboratory procedures [10], particularly in Analog Electronics course. The practical experience acquired in a physical laboratory is vital for the testing and analysis of analog circuits, which are fundamental elements of engineering education. In traditional hands-on Analog Electronics laboratories, students often face significant difficulties when constructing electronic circuits using a breadboard. Although breadboard is a reusable platform to assemble electronics components without soldering and for initial circuit testing, some students are not capable to troubleshoot and find error within a given time for complex analog circuits, e.g. BJT small-signal amplifiers.

In typical Analog Electronics laboratory courses, investigation of difference and instrumentation amplifiers laboratory system is proposed in [11]. The laboratory complexity can be increased by requiring the students to do simulations as pre-lab activity, verify the circuits using breadboard, solder and test the printed circuit board (PCB) as implemented in [12]. Over the years, many manufacturers commercially produce laboratory trainers for educational purposes. However, they do not always provide transparency and limit students' ability to observe the real hardware components inside the product's enclosure.

This paper presents an educational trainer board for BJT small-signal amplifiers, utilizing EasyEDA for the design of the PCB to connect virtual and physical laboratories. EasyEDA is a web-based EDA tool suite [13] that enhances the PCB design process by providing cloud-based accessibility, collaborative functionalities, and a user-friendly interface. This facilitates the transition from virtual 2D and 3D representations to practical and fabrication work. The software encompasses a comprehensive set of tools for drawing schematics, wherein components such as resistors, capacitors, and transistors are represented by their corresponding symbols and accurate dimensions. Thus, this multifaceted approach ensures that students are well-prepared to apply their knowledge in both virtual and physical laboratory settings.

II. Virtual Laboratory of BJT Small-Signal Amplifiers

Small-signal operation is the analysis of amplifiers that take a very small amplitude signal in the range of a few millivolts and produce large output signal in the range of several volts. In the laboratory experiments, students will evaluate the behavior of three common configurations of BJT small-signal amplifiers (i.e., common-emitter (CE), common-collector (CC), and common-base (CB)). All the amplifier circuits are voltage-divider bias. Only the CE circuit uses a bypass capacitor.

There are two methods to analyze the dc bias values of a voltage-divider BJT small-signal amplifier circuit, either using exact or approximation methods. Based on approximation method, the base voltage, V_B can be calculated by:

$$V_B = \frac{R_2}{R_1+R_2} \times V_{CC} \tag{1}$$

where V_{cc} is the DC voltage supply.

Then, the emitter voltage, V_E and emitter current, I_E are calculated by:

$$V_E = V_B - V_{BE} \tag{2}$$

$$I_E = \frac{V_E}{R_E} \tag{3}$$

The r_e transistor model can be determined by:

$$r_e = \frac{26\ mV}{I_E} \tag{4}$$

The overall ac voltage gain, A_{VWL} when the output is connected with a load resistor, in all amplifier circuits is calculated by:

$$A_{VWL} = \pm \frac{V_{out}}{V_{in}} \tag{5}$$

where input voltage, V_{in} and output voltage, V_{out} can be both rms, peak, or peak-to-peak values.

The following are the objectives, the materials needed, and the procedures for the BJT small-signal amplifier experiments in Analog Electronics laboratory module for second-year Bachelor of Electrical Engineering students in Universiti Teknikal Malaysia Melaka. The current implementation is to conduct hands-on experiments and use hardware components and equipment, without any simulation task.

Objectives of experiments:

After performing the experiments, student will be able:

1) To construct various configurations of transistor amplifiers.
2) To determine the output voltage, V_{out} of the transistor amplifiers according to the configuration.
3) To evaluate the effect of load resistor, R_L on the voltage gain, A_{VWL}.
4) To verify the behavior of the transistor amplifiers.

Equipment / Components required:

Oscilloscope, Digital Multimeter, Function Generator, DC power supply, Breadboard/Trainer. A list of components is given in Table I.

TABLE I. List of Components

Resistors:	Capacitors:	Transistor:
(1) 1.5 kΩ (1) 3.6 kΩ (2) 10 kΩ (1) 33 kΩ	(2) 47 µF, 25V (1) 100 µF, 25V	(1) NPN 2N2222

In this paper, Tinkercad online circuit simulator is used as a part of the methodology for testing the amplifier circuits virtually. It allows students to virtually assemble analog systems and components, including breadboard, DC and AC power supplies, function generator, and oscilloscopes, thereby reducing the time needed to grasp the fundamental concepts of analog electronics. This approach allows for iterative design processes where students can explore different circuit configurations, troubleshoot issues, and refine their circuits without damaging physical components. The virtual simulation serves as a preliminary step before moving on to the experiment testing using the proposed trainer board.

In the experimental procedure, a 12 V DC voltage supply is provided to an amplifier circuit, as illustrated in the block diagram of Fig. 1. The input terminal of the amplifier network is applied with an AC input voltage, V_{in} of 40 mV peak-to-peak (V_{pp}) amplitude with frequency, f of 1 kHz. Students are required to observe the output voltage, V_{out} waveform across the load resistor, R_L using an oscilloscope. The experiment requires monitoring and recording both the measured peak-to-peak input voltage, V_{in} and the output voltage, V_{out} waveforms.

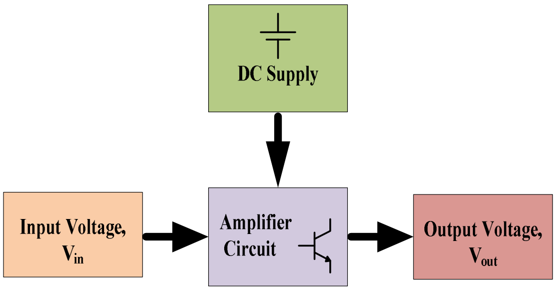

Fig. 1. Block diagram of amplifier circuit.

In circuit analysis, students will calculate the voltage gain, A_{VWL} for each transistor amplifier configuration by considering the load resistor after capturing the waveforms. This process allows students to assess the amplifier's behavior in terms of voltage gain and determine the influence of the amplifier circuit on the output voltage, V_{out} signal. Tinkercad's sophisticated simulation capabilities provide an accessible platform for students to conduct hands-on experiments in a virtual laboratory setting. By simulating the amplifier circuits in Tinkercad, the study provides a foundational understanding of circuit behavior, enabling a smoother transition to physical experimentation. The simulated results, particularly the voltage gains of the amplifier circuits are recorded and later compared with the experimental results obtained from the actual trainer implementation.

A. *Common-emitter amplifier circuit*

The most frequently encountered transistor configuration that appears in Fig. 2 is called the CE configuration. CE amplifier circuit exhibits high voltage gain and high current gain. It is important to note that the base terminal is applied with input voltage, V_{in} of 40 mV_{pp} with frequency, f of 1 kHz, and the collector terminal is used to extract the output signal. C_1 and C_2 are coupling capacitors, meanwhile, C_3 is a bypass capacitor. The bypass capacitor increases the signal voltage gain of the CE circuit.

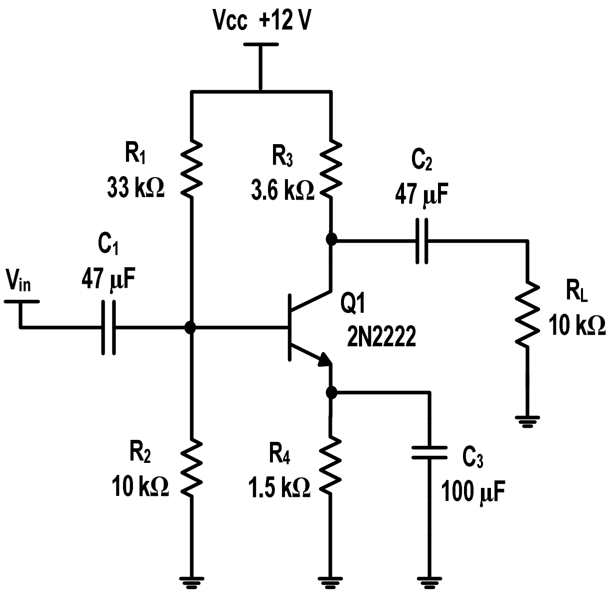

Fig. 2. Common-emitter (CE) amplifier circuit.

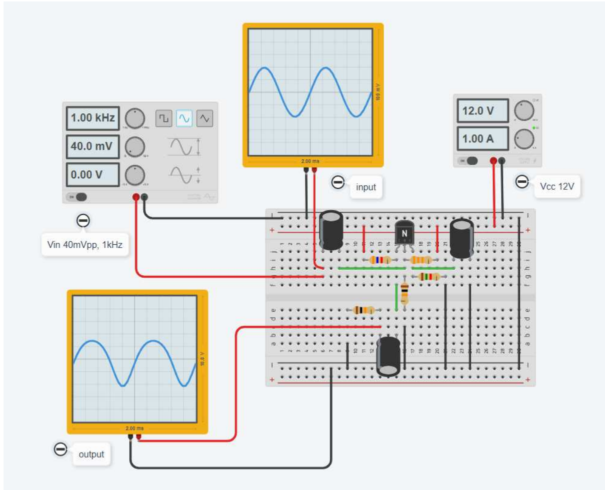

Fig. 3. Common-emitter (CE) amplifier circuit in Tinkercad.

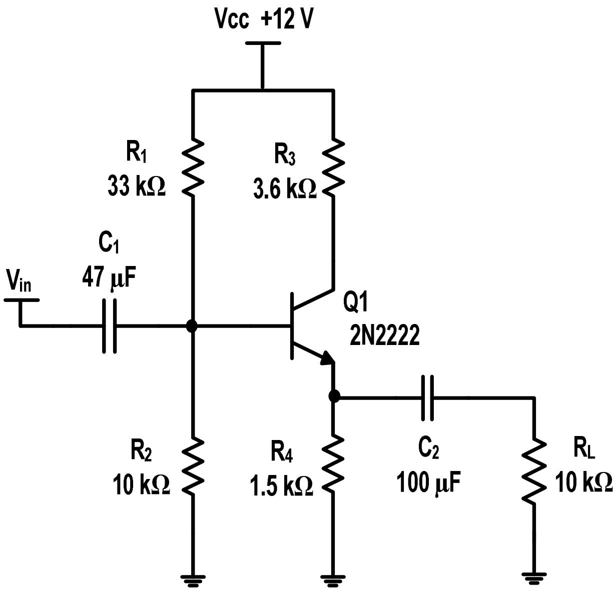

Fig. 4. Common -collector (CC) amplifier circuit.

The CE amplifier circuit is implemented using Tinkercad as shown in Fig. 3. From the simulation, the input and output voltages (V_{in} and V_{out}) are measured by oscilloscopes. In this simulation, the measured output voltage, V_{out} approximates 3.8 division × 10 V/10 division = 3.8 V_{pp}. Normally, the phase difference between input and output voltages is 180° or out of phase. However, a limitation of Tinkercad in simulating the CE circuit is it does not show the phase shift response of the output voltage when compared with the input voltage.

B. *Common-collector amplifier circuit*

Fig. 4 illustrates the CC amplifier circuit, which is frequently referred to as an emitter-follower. The base terminal is connected to a coupling capacitor, C_1 which applies the input voltage, V_{in} of 40 $mV_{pp}$with frequency, f of 1 kHz. The output is located at the emitter terminal. The operation of the CC amplifier circuit is demonstrated in Tinkercad as seen in Fig. 5. No phase conversion could be observed, and the CC amplifier's output voltage is approximately equal in amplitude to the input voltage. In the simulation, the measured output

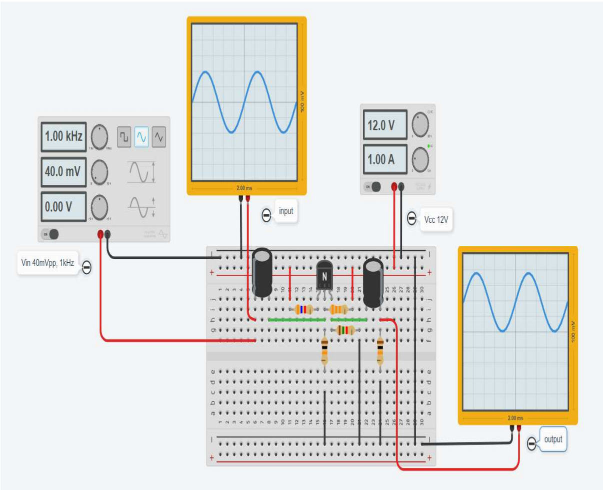

Fig. 5. Common-collector (CC) amplifier circuit in Tinkercad.

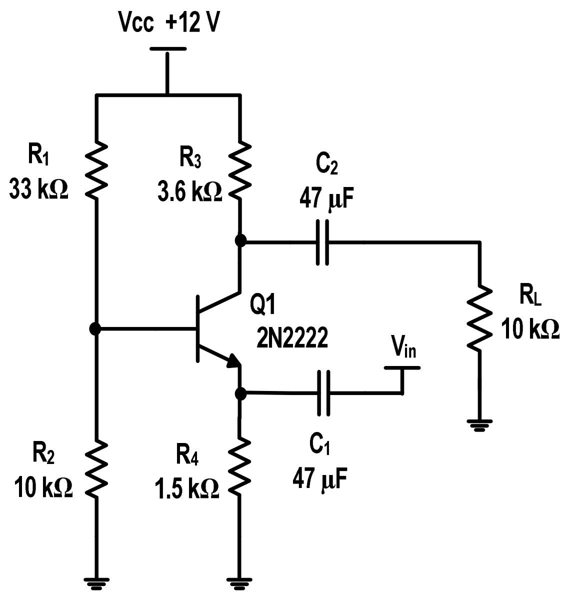

Fig. 6. Common-base (CB) amplifier circuit.

voltage, V_{out} approximates 3.8 division × 100 mV/10 division = 38 mV_{pp}. As a result, a CC amplifier has a voltage gain of about 1, and its output voltage is almost identical to its input value in terms of both amplitude and phase.

C. Common-base amplifier circuit

The third configuration, which is CB configuration with voltage-divider bias, is presented in Fig. 6. In the CB amplifier configuration, the input voltage, V_{in} of 40 mV_{pp} with frequency, f of 1 kHz is applied to the emitter terminal, and the output signal is taken off from the collector terminal. The CB circuit is implemented using Tinkercad as illustrated in Fig. 7. In this simulation, the measured output voltage, V_{out} approximates to 5.8 division × 4 V/10 division = 2.32 V_{pp}. No phase inversion occurs between input and output voltages, as anticipated for a CB amplifier circuit.

III. Proposed Trainer for BJT Amplifier Circuits

In this section, the proposed method for designing a BJT amplifier trainer board using EasyEDA software is outlined, focusing on creating a practical and user-friendly educational

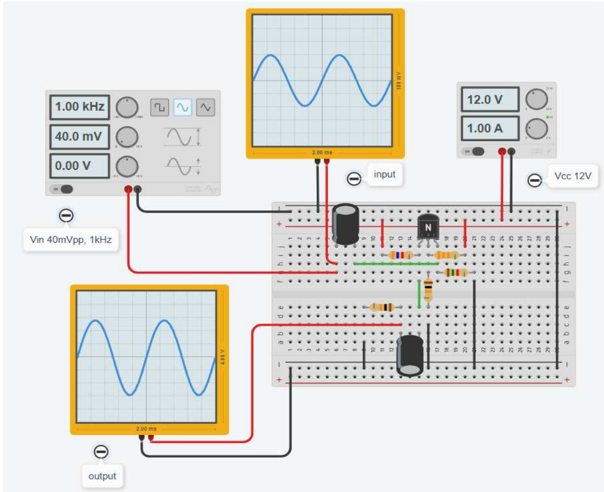

Fig. 7. Common-base (CB) amplifier circuit in Tinkercad.

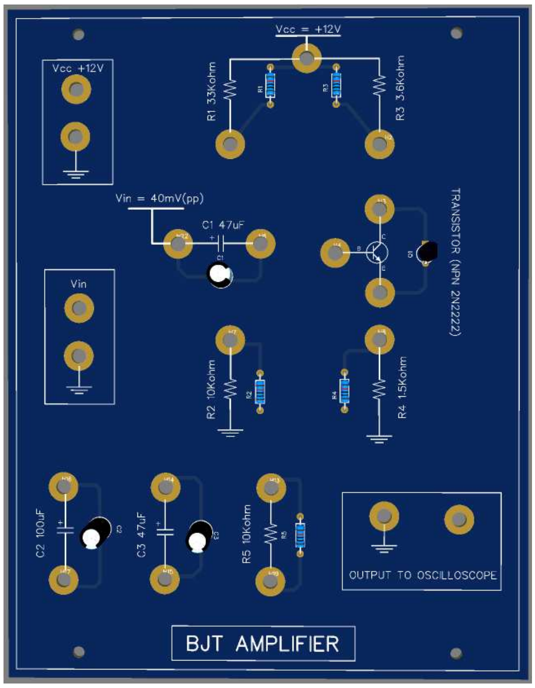

Fig. 8. The 3D view of BJT amplifier trainer board in EasyEDA.

tool for students. The trainer board is designed to minimize common errors in circuit assembly and enhance students' understanding of BJT amplifier concepts by providing a reliable, pre-built platform. The final 3D view shown in Fig. 8 is a robust and reliable BJT amplifier trainer board that students can use to perform experiments without the typical challenges of breadboard wiring. The proposed trainer board clearly labels component names and values, streamlining the hands-on learning experience and ensuring that students can engage with the material more effectively.

The process begins with the development of a PCB for the BJT small-signal amplifier. The design procedure for the hardware begins with the production of an amplifier circuit schematic diagram created with EasyEDA software. This schematic diagram serves as the blueprint, defining how each component is interconnected to achieve the desired amplification output. Once the schematic diagram is finalized in EasyEDA, the PCB layout editor is used to transform the schematic into a physical circuit design. In this step, the components are placed on a virtual PCB, and the software automatically routes the copper traces that connect the components according to the schematic diagram. The layout editor allows for precise placement of components and routing of traces on both the top and bottom layers of the PCB, ensuring an optimal path for electrical signals and preventing electrical shorts.

After finalizing the PCB layout, the design is exported as Gerber files, which are industry-standard files used by manufacturers to fabricate PCBs. These files include detailed information about the copper traces, component placement holes, and other essential features of the PCB. The Gerber files ensure that the manufactured PCB precisely matches the design specifications created in EasyEDA. In addition, it also serves as a one-stop solution for PCB manufacturing, where designers can effortlessly upload their designs, receive instant quotes, place orders within minutes, and track their orders in real-time via the EasyEDA website [13].

IV. Results and Discussion

Fig. 9 shows the experimental setup of the BJT amplifier's hardware prototype. The principal functionalities of the prototype are as follows: the trainer board hosts the circuit components, while the GW Instek GFG-8020H function generator and GW Instek SPS-606 DC power supply, respectively provide the necessary AC and DC input signals for the testing, and the Tektronix TDS2024C digital oscilloscope was used to measure the varying input and output voltages waveforms for analysis of circuit's operation. Observations have been done on the input and output waveforms from the practical experiment using the trainer board and compared to the simulated waveforms from the Tinkercad simulation. The results from the Tinkercad simulation and actual hardware measurement using the trainer board were measured and recorded as depicted in Table II.

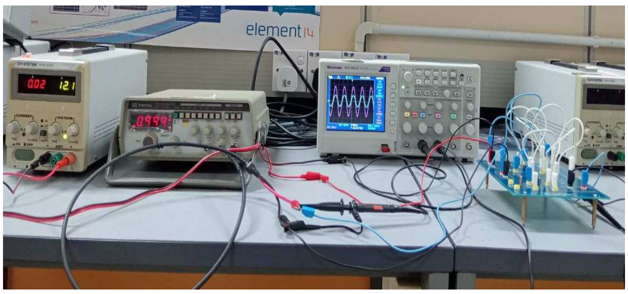

Fig. 9. Experimental setup of BJT amplifier circuit.

TABLE II. Voltage Gain of BJT Amplifiers

Configuration type		V_{in} (V_{pp})	V_{out} (V_{pp})	Voltage Gain (A_{VWL})
CE	Tinkercad Simulation	40 m	3.8	-95
	Hardware	40.8 m	4.96	-121.57
CC	Tinkercad Simulation	40 m	38 m	0.95
	Hardware	40.8 m	40 m	0.98
CB	Tinkercad Simulation	40 m	2.32	58
	Hardware	40 m	2.1	52.5

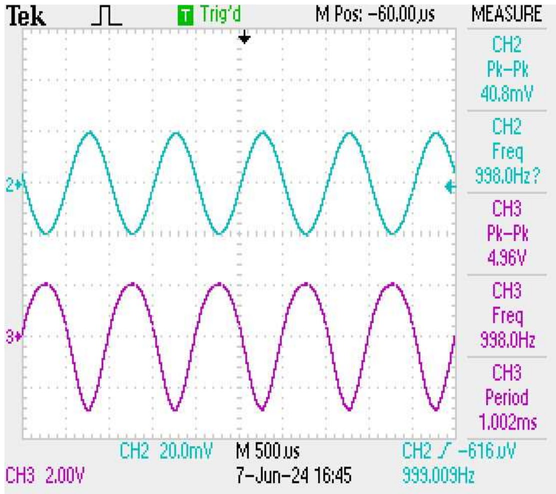

Fig. 10. Experimental result of CE amplifier circuit.

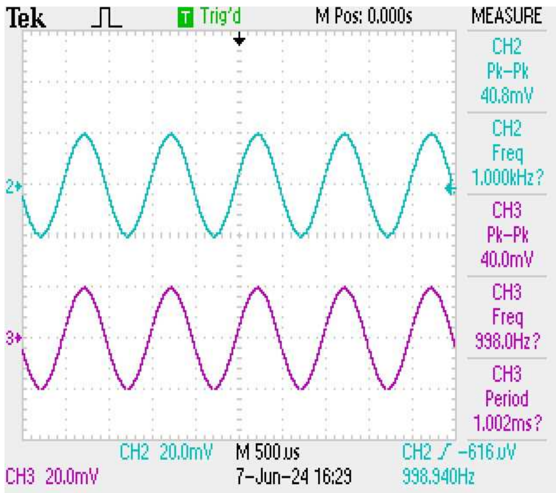

Fig. 11. Experimental result of CC amplifier circuit.

Fig. 10 demonstrates that the CE amplifier's output voltage waveforms are out of phase with the input based on the phase shift of 180°. Both the voltage gains for CE amplifier are expected to be negative sign due to inversion of the output voltage when compared with the input voltage. Besides, the output voltage waveform from the practical experiment and Tinkercad simulation were quite similar to the input voltage waveform for the CC amplifier's result as shown in Fig. 11. Moreover, the output voltage waveform of the CB amplifier from practical experiments and Tinkercad exhibited significant similarity, with the output being in phase with the input, as depicted in Fig. 12. Consequently, voltage gains are positive in the CC and CB configurations because the input and output voltages are in phase.

From the findings, it is shown that the BJT amplifier trainer board gives several benefits during the lab experiment. First and foremost, trainer board provides a clean and organized design, making troubleshooting to be easier than using conventional breadboard. Since the trainer board has the components values and names on it, it is much easier to understand the position of the electronic components such as resistor, capacitor and transistor. This trainer helps to shorten up the duration to complete laboratory tasks. Overall, the

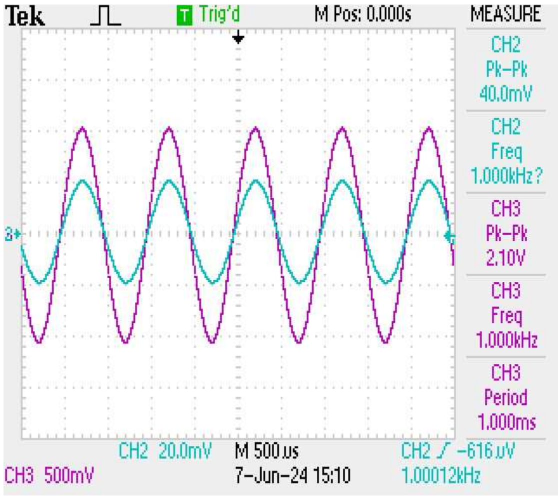

Fig. 12. Experimental result of CB amplifier circuit.

understanding of Analog Electronic course is successfully being strengthen with the help of virtual lab using Tinkercad and the trainer board.

V. Conclusion

This effort underscores the significance of integrating simulation tools, like Tinkercad, with conventional laboratory experiments of analog electronics circuits. This study has effectively proved the feasibility of developing an educational and practical BJT amplifier trainer board by utilizing EasyEDA for hardware design. The integrated methodologies substantially improve the learning experience by enabling students to visualize and simulate circuit activity in a virtual setting prior to practical engagement with actual hardware components.

Tinkercad facilitates the transition from theoretical learning to practical application, enabling students to comprehend schematic designs more readily prior to developing circuits on the trainer board. Implementing a printed BJT amplifier circuit in laboratory experiments provides notable benefits, especially in the context of complex circuits. The utilization of a PCB streamlines the circuit-building process, enhancing clarity and significantly decreasing the time needed in comparison to assembling circuits on a breadboard. This trainer board effectively functions as an educational tool, enhancing students' comprehension of circuit operation in BJT small-signal amplifier applications. Utilizing the trainer board enables students to concentrate on understanding and implementing circuit principles without the distractions of manual wiring errors or the potential for component damage. This approach improves the educational experience and also equips students for more complex circuit design and analysis tasks in their future studies. Future work will explore other types of analog electronics circuits for laboratory applications.

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