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Experimental Works on Short Range Communication Systems Using Photovoltaic Based Receiver

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Abstract: A lot of research has focussed on LED lights to move technology forward in the visible light communication field. Due to their properties which include high efficiency, high luminance, reliability, long life time, low energy consumption and cost savings, white light LEDs are expected to be the next generation of lamp and communication systems. White light LEDs have dual functions; they illuminate rooms and have applications in optical wireless communication systems. In this study, the fundamental experiment was carried out to study the ability of white LEDs to be used as the transmitter with a photocell as the receiver. The LED worked as the transmitter and transmitted the modulated audio signal via open space to the receiver. The photocell worked as the transducer and once it was connected to the amplified speaker, the original audio signal could be heard. The results from these experiments showed that high frequency could enhance the ability of white LEDs to be used for data transmission with the ability to hear the output audio signal up to 50 cm from the transmitter to the receiver.

Key words: Visible light communication, white LED, photocell, optical wireless communication, modulated audio signal, open space

INTRODUCTION

Visible light communication is the most advanced communication technology that uses visible light between 400 and 700 THz. This latest technology has used light to transmit information that is visible to the human eye. There are many devices that use white light including light fixtures in offices, homes, commercial displays, traffic lights and electronic home appliances such as televisions and computers. Recently, all the devices have been fabricated using LEDs (Light Emitting Diodes) because the LEDs have low power consumption and a long life span. LED lighting has been considered a green technology because it has a reduced contribution to the carbon footprint. LEDs have special characteristic; the light turns on and off very fast. Because of this characteristic, data could be transmitted by lighting a LED on and off at ultra speed. These findings could be developed to replace the current communication technology that uses radio waves. In the field of communications, there has been use of wireless communication using radio waves. Although, radio waves have been widely used around the world due to weakness and other limitations, researchers have been exploring visible lighting as a new medium of communication. Research has focused on LEDs which have been expected to serve in the next generation of lamps. LEDs offer advantageous properties such as brightness, reliability, lower power consumption and a long lifetime (Komine and Nakagawa, 2004). These devices have not only been used for illuminating rooms but also for optical wireless communication systems (Komine and Nakagawa, 2004). This type of system has been expected to be the indoor communication method of the next generation.

Today among all wireless communication schemes, transmission using either radio waves microwaves has dominated. This domination has been primarily due to the availability of high-sensitivity receivers and the ability to provide either broad coverage at low frequencies or line-of-sight propagation at high frequencies. However, RF can support only a limited bandwidth because of the restricted spectrum availability and interference (Singh *et al*., 2002). The radio frequency interference has thus degraded user connectivity in terms of throughput,

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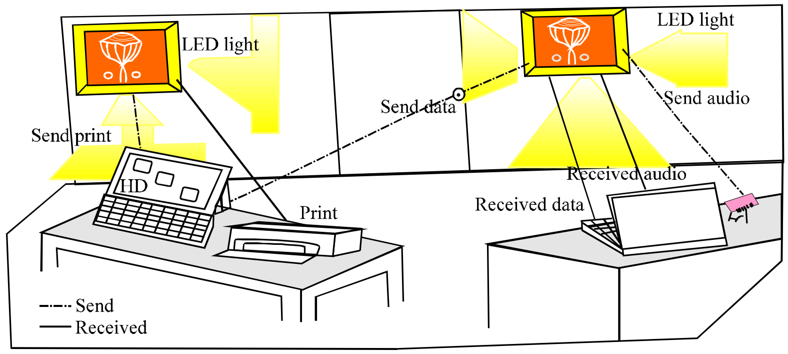

Fig. 1: Indoor communications: Using visible light communication with embedded transmitters and receivers in each of the pieces of electronic equipment

link quality and range. Position detection with cellular telephones and car navigation systems that use radio waves has not been very accurate as there has been some difficulty in identifying the exact location of the information terminal. This drawback becomes more pronounced when the equipment is used in underground shopping malls or inside buildings. The use of radio frequencies have been prohibited in hospitals and on flights because the interference disturbs the precision of the equipment and devices (Shun *et al*., 2007). Visible light in the Electromagnetic (EM) wave spectrum has been considered to be a potential solution to combat the plights faced by RF.

The purpose of this proposal was to develop a communication system for the next generation using visible light. This system could be implemented through the application of photocells as a photodetector to absorb the illumination of LEDs and turn that illumination into electricity. By using solar cells to transmit the signal, the overall system's cost reduction could be reached at an optimized level. Moreover, the system could use LEDs as a source of illumination and as a medium for indoor communications such as in Fig. 1. Therefore, the LEDs could have a dual-function, replacing the current lamps for effective illumination and the radio waves for a wireless communication medium.

Literature review/analysis: A fundamental analysis done on visible light communication came to the conclusion that visible light communication was expected to be the indoor wireless communication of the next generation due to the possibility of transmitting at a high data rate (Komine and Nakagawa, 2004; Tanaka *et al*., 2001).

In this research, they also discussed reflection and intersymbol interference. Based on this analysis, they found that communication performance was degraded severely by intersymbol interference (Tanaka *et al*., 2001). Intersymbol interference depended on the data rate and the Field of Receiver (FOV) because the LED lights were distributed within a room and the irradiance of light was wide for the function of the lighting equipment. Research done by Takakuni Douseki on the batteryless optical-wireless system with white-led illumination showed the system's ability to transmit data at the speed of 100 Kbps with the distance of 40 cm.

This system successfully performed without a battery. This system used the white LED as the transmitter and the photocell as the receiver (Douseki, 2004). Deqiang *et al*. (2007) carried out the numerical simulations for an optimal lights layout scheme for the visible light communication to find the effectiveness of this communication system. There were two kinds of communication systems being proposed, an optical up-link and an optical down-link.

The up-link had a small, superficial area and narrow angle of irradiance like an electric torch whereby the LED could be lighted from the bottom to the top. Generally, the down-link system had a large superficial area and wide angle of irradiance because the light was located at the ceiling and lighted from the top to the bottom. The performance of the visible light communication was analysed using the optimal lights layout scheme in terms of the received power and bit error rate (BIT). Based on the numerical simulation results, the received power was very large compared to the infrared wireless communication which could make broadband communication possible (Deqiang *et al*., 2007). The effectiveness of the light layout was analyzed based on the received power.

From the results of the simulation of the optimal lights layout scheme for visible light communication, they concluded that this technique could be applied to obtain an excellent performance. A study on the challenges and possibilities of visible light communications was done by

O'Brien *et al.* (2008) which introduced the principles of VLC and outlined some of its major challenges. The research was an overview of the applications of visible light communication. In this study, problems with the implementation of these communication systems were highlighted.

The problems that were raised included the limited bandwidth of LEDs that would affect the high speed communication, the low bandwidth of the transmitter, the disadvantages of the transmitter equalisation, providing an up-link to the distributed transmitter structures and the visible light communication was subjected to regulations by non-communication standards (O'Brien *et al.*, 2008).

Modulated led: The audio signal could be carried by visible light through wireless channels using optical modulation. The modulated signal carried on a beam of light could be used for long-haul communications and high bandwidth communication lines. The electromagnetic waves would be carried by particles known as quanta. Quanta of higher frequency waves carry more energy than the lower frequency fields. This ability to carry more energy was why the visible light was able to carry more information than the radio waves. Two principal light sources that have often been utilized for fibre communication applications include heterojunction-structured semiconductors known as Laser Diodes (LD) and Light Emitting Diodes (LEDs).

The major difference between LEDs and LD is the optical output. LEDs optical output is incoherent whereas the LD is coherent. The output radiation of LEDs has a broad spectral width and thus large divergence beam while LDs optical output is very directional and monochromatic. The circuitry to drive LEDs was less complex and no thermal or stabilization circuit was needed.

Intensity modulation: In optical communications, intensity modulation has been a form of modulation where the optical power output of a source was varied in accordance with some characteristic of the modulating signal. Optical sources do not have the discrete upper and lower sideband terms b ecause of the lack of sufficient coherence to produce them.

The envelope of the modulated optical signal is an analogue of the modulating signal in the sense that the instantaneous power of the envelope is an analogue of the characteristic of the interest in the modulating signal. Recovery of the modulating signal was by direct detection not heterodyning. According to Cox *et al.* (1997),

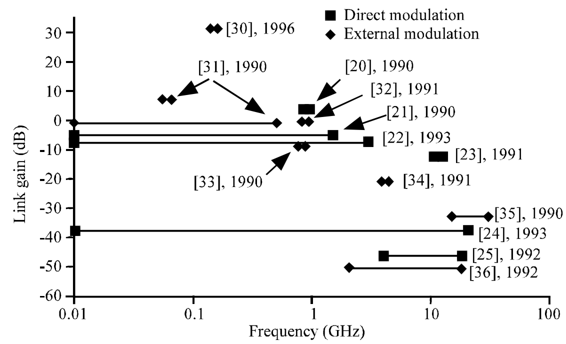

Fig. 2: Summary of the direct and external modulation link gains

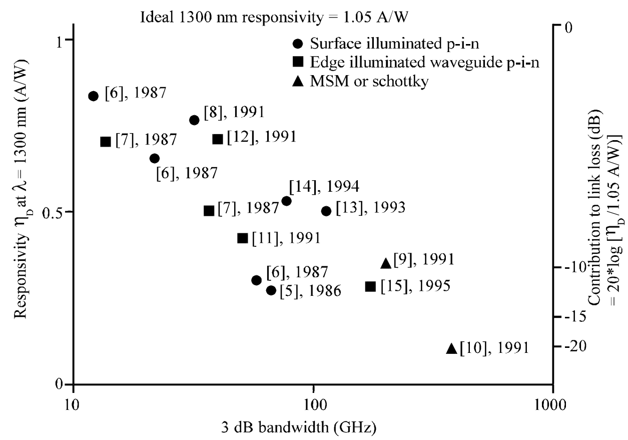

Fig. 3: Responsivities and 3 dB bandwidths of state-of-the-art photodetectors (Cox *et al.*, 1997)

techniques and performance of intensity-modulation direct-detection analogy optical links, Fig. 2 was the summary of the direct and external modulation-links gain. An important conclusion drawn from the graph below was that the maximum bandwidth of the direct modulation links was roughly 20 GHz.

Photodetectors: Photodetectors work as the receiving devices that interpret the information contained in the optical signal, sensing and converting the luminescent power falling on them into a correspondingly varying electric current. Today, the commonly used semiconductor photodetector is the pin structure. Figure 3 is the summary of the reported results of 1300 and 1550 nm wavelength avalanche photodiodes as evidence that photodetectors were available with 3 dB bandwidths which were more sufficient for most link applications (Cox *et al.*, 1997). However, the highest bandwidths came at a penalty to the detector responsivity (Cox *et al.*, 1997). Ideally, at any optical wavelength, the responsivity of any photodetector is simply the electron charge divided by the photon energy (where h is Planck's constant and c is the speed of light in a vacuum). Based on Fig. 3 at 1300 nm, the responsivity worked out to about 1.05 A/W. From there, the frequencies were varied in the low frequency range and the fibre-coupled responsivity at 1300 nm for the photodetector was 0.9 A/W which contributed 1.3 dB to the link Rf-to-RF loss (Fig. 3). However at higher frequencies, the typical photodetector responsivity of 0.1 A/W would contribute 20.4 dB to the link loss. The photodetector responsivity decreased for higher frequencies due to the limited surface-illuminated configuration that made the photodetector volume less efficient at absorbing the light.

The other photodetector trade-off was between linearity and optical power. Intensity modulation direct detection links operated at high optical power as the direct modulation and external modulation had a relation on. The external modulation and the link gain was proportional to the square of optical power whereas for direct modulation, the maximum modulation frequency of the diode lasers was proportional to the square root of optical power (Way, 1987; Williams *et al*., 1996). However at high optical power densities, the photodetector nonlinearities began to dominate the modulation-device nonlinearities.

The photodiode nonlinearities reduction could be achieved by increasing the bias because at high detector currents, the series resistance or space-charge effects reduced the fraction of the bias voltage by creating a field across the junction at higher optical powers. At low frequencies, the photodetector was nearly ideal in terms of linearity, power handling and reponsivity but it was not useful because of the limited reponsivity and optical power density. A significant reduction of the linearity/power density conflict could be achieved by changing the photodetector illumination geometry.

Photocell: According to the research, fabrication and test of an efficient photovoltaic cell for laser optical power transmission by D'Amato *et al*. (1992), the efficiency of power conversion of optical to electrical was measured to be in the range of 55-59% when the photocell was illuminated by a monochromatic light. The laser diode source at this efficiency range was at 826 nm wavelength and the intensities were up to 54 W cm^{-2}. The devices performance showed that there was no sign of degradation at high optical intensities.

Photocells have been a catch-all category for a wide range of devices that operate based off exposure to photons or electromagnetic energy. They have also been called photosensors and photodetectors. There have been many types of photocells such as photovoltaic, photoresistor, phototransistor, photodiode, golay cell, photomultiplier and charge-couple devices. All of these photocells have their own function for implementation. Photovoltaic refers to a device that converts solar energy into electrical power.

Once the light shines on the cell, the photon will knock the electrons on the cell to a higher state of energy and produce a usable current. Photoresistors have also been known as a photoconductors or light dependent resistors. Photoconductors are a type of resistor that decrease resistivity after exposure to the light.

Photodiodes are light-activated semiconductor devices that allow current to flow in only one direction. Phototransistors are semiconductor devices that have high sensitivity for light and allow for bidirectional current flow and are used frequently in amplifying and switching applications.

If phototransistors are highly sensitive to light, the photomultiplier is even more so. A golay cell is used for radiation of infrared detection whereas the charger coupler device is a type of photosensor that is extremely reliable and accurate. The charges produced by photosensitive sensors are used to analyze a range of things, from galaxies to single molecules.

In this study, we focused on the experimental research of visible light communications using a photovoltaic as the photodetector. From the experiment, we found that photocells work as the photodetector that could change the light into electricity and finally convert it into an audio signal.

MATERIALS AND METHODS

Transmitter and receiver circuit: As shown in Fig. 4, this communication system could be divided into two parts; 1st is the transmitter and the 2nd is the receiver. Focusing on the transmitter circuit, an input signal will be injected in a driver circuit and will be changed to a light signal using the light source (LED). Then, the signal will be transmitted through the open space medium to the

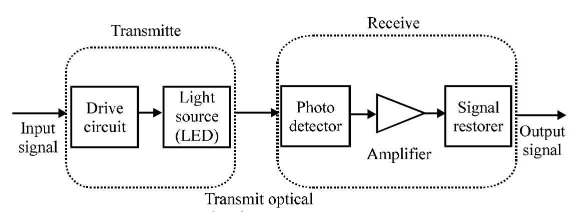

Fig. 4: The overall diagram visible light communication system

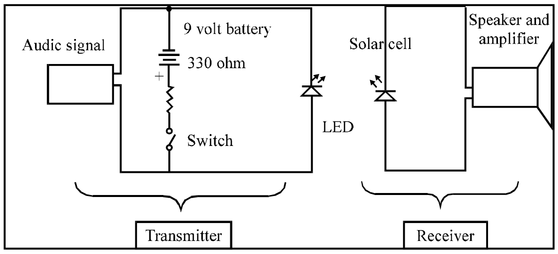

Fig. 5: The experimental circuit of transmitter and receiver

receiver. The receiver basically consists of the photovoltaic as the photodetector, amplifier and signal restoring circuitry. The photodetector sensed the luminescent power hitting it and converted the variation of the optical power into a correspondingly varying electric current. The optical signal generally had a large divergence beam when it emerged from the LED light. An amplification of the optical signal and signal restoration could be done to get a clear output signal. Figure 4 is an overall diagram of the communication system using air as the medium.

In this study, some modifications of the communication system were made through simple experimental researches. In this experiment, the transmitter was designed using five components. The 1st component which was a super bright white LED was used as the modulator.

By knowing the specification of the super bright LED, a simple circuit was designed as shown in Fig. 5. LEDs worked to modulate the amplitude of the light based on the amplitude of the audio signal. Through a standard 3.5 mm audio jack, the audio signal which was fed to the circuit was sent to the 330 Ω resistor, switch and 9 Volt battery.

The source of the audio signal was injected from the radio that was equipped with a built-in amplifier. The LED was provided by a steady DC current by the battery and under the effects of the battery alone, the LED glowed with a fixed brightness.

The resistor functioned to limit the current so the LED did not burn out whereas the switch functioned to turn on/off the LED. Figure 6 shows the experiments that had been carried out in the lab. For the 2nd part of this system, the receiver was built using a solar cell and a speaker with a built-in amplifier. The solar cell played the role of a transducer in this system and it was connected to the earphone jack.

The earphone jack was inserted to the input jack of the amplified speaker to get the output audio sound. Weak fluctuating radio signals were added to the

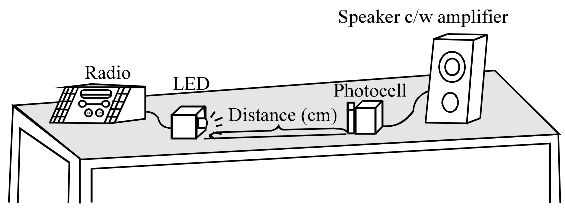

Fig. 6: The radio connected to the LED to modulate the audio signal; whereas the photocell was connected to the speaker to get the original audio signal that was sent

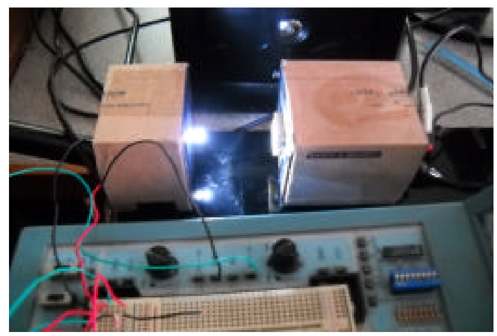

Fig. 7: The LED and the photocell is arranged in the horizontal position

constant signal from the battery after the audio jack was connected to the audio source. The LED still glowed but then it blinked in synchronisation with the audio signal as the amounts of the current passing through it varied.

Electrical signals were generated when the blinking light hit the solar cell. This signal varied in synchronisation with the original audio signal. Then, the signals were fed to the speaker embedded with the amplifier, recreating the original sounds from the audio source.

The LED blinked when the low frequency was injected to the LEDs but for high frequencies, the flicker was so fast that it was undetectable with the human eye. This is because the rate of modulation would be millions of times faster than a human eye can see.

The experiment shown in Fig. 7 used the function generator to replace the battery. The LED and photocell were placed facing each other horizontally. The purpose was to study the output power converted by the photodetector into electricity and demodulated into an original audio signal.

The distance was varied as can be seen in Fig. 7 and 8 to study the ability of the LED light transmitting the audio signal at a specified distance.

Fig. 8: The experimental setup to test the largest distance that the LED

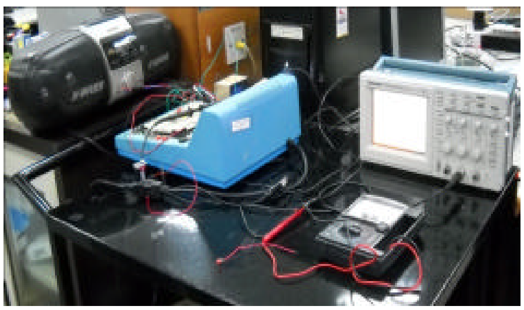

Fig. 9: The set up of an experiment to study on the relationship between output power (dB) and the frequency (kHz)

Figure 9 is the experimental setup for data collection of frequency (kHz) and output power (dB). The result of the data collection is shown in the graph of result section.

RESULTS AND DISCUSSION

Distance (cm) versus output voltage (V): The constructed 1st circuit was tested in the laboratory to analyze the characteristics of the designed circuit. The circuit was tested by varying two parameters, the circuit was tested to easily analyse the characteristics. Those two parameters were distance and frequency. The voltage characteristics were analysed by varying the distance as shown in Fig. 10. The early reading of output voltage at the photodetector were taken before an experiment was carried out. This step was done to get the voltage value of the surrounding luminance effects on the receiver. As the distance between the LED light and the photodetector increased, the value of voltage became decreased.

This showed that the voltage was inversely proportional to the distance. The audio signal could be heard clearly in the 1st 50 cm. The signal quality decreased as the distance of photodetector and LED kept increasing. At 60 cm from the transmitter, the audio signal was not clear because the intensity of the light

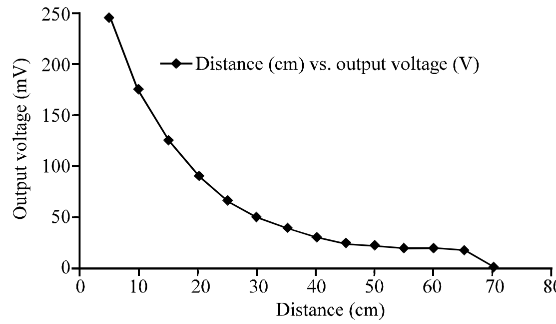

Fig. 10: The graph is the output voltage(mV) versus distance (cm)

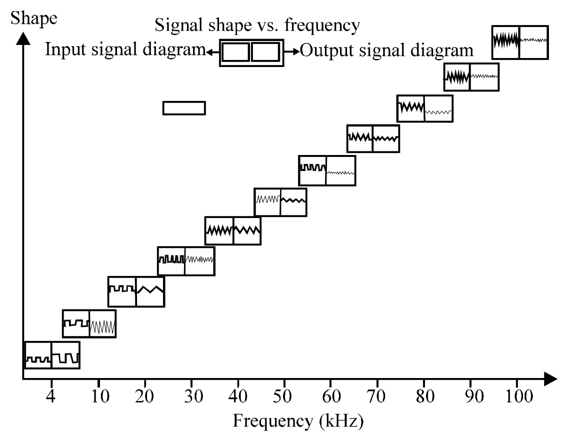

Fig. 11: The graph of signal shape input/output vs. frequency

was too poor. The intensity of the LED lights that hit on the photodetector became weaker because the characteristics of LED light had a large divergence angle as the distance increased. The ampliflier played a large role in both the transmitter and receiver sides which allows it to make the distance larger.

Power versus frequency characteristics: Based on the observations of the experimental researches, a graph of signal shape versus frequency was shown as in Fig. 11. From this graph, the changing frequency does influence the signal waveform. At the lowest frequency 4 kHz, the input signal waveform was in the rectangular waveform and the output waveform was a distorted rectangular waveform.

However at the 10 kHz onwards, the output waveform changed. Instead of the distorted rectangular waveform at 10 kHz and so forth the output shape changed to triangle waveform. The noise distortion had made the input rectangular waveform change to triangular waveform at the output. The changes between the input and output waveform were obviously seen as the frequency increased. Figure 12 showed the signal of input and output waveform corresponding with the

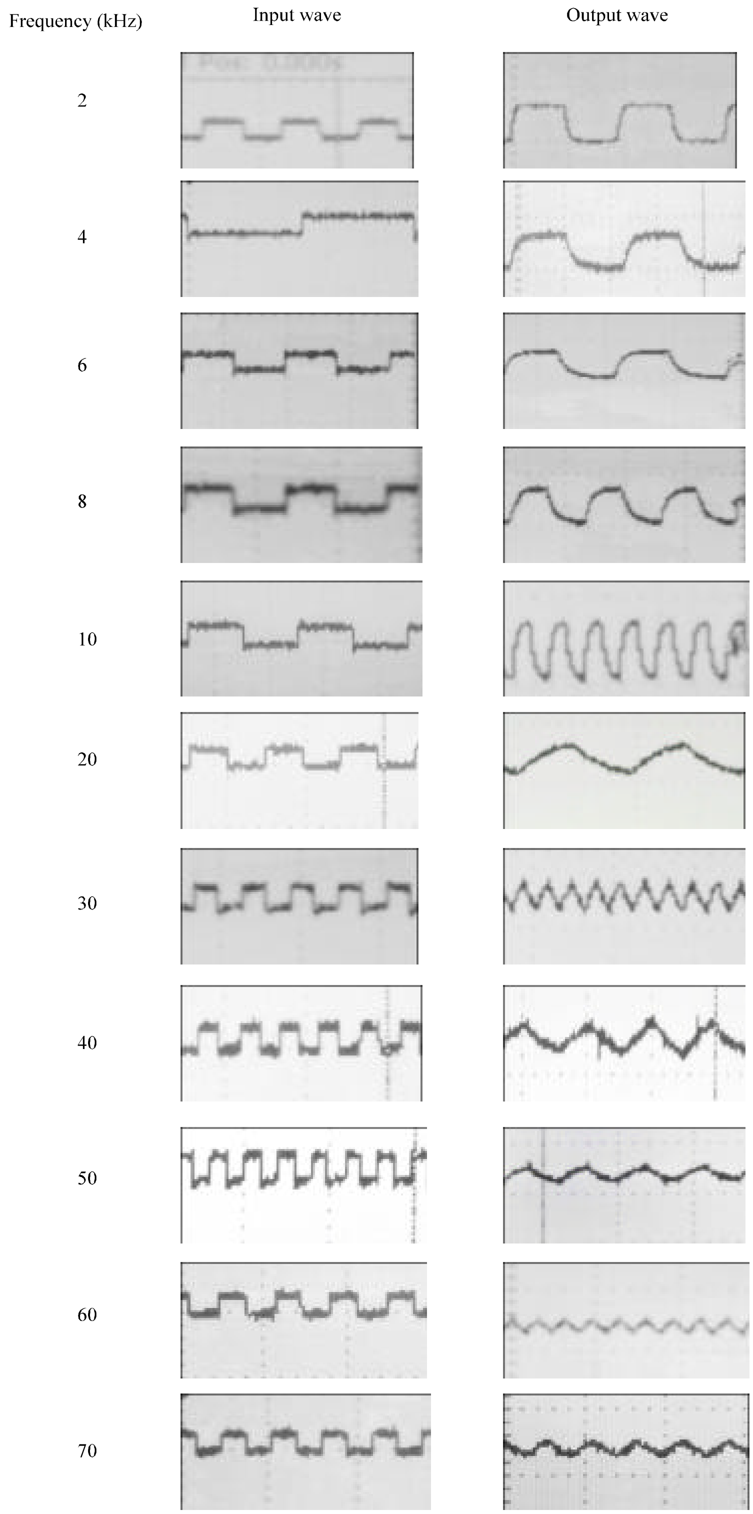

Fig. 12: Continued

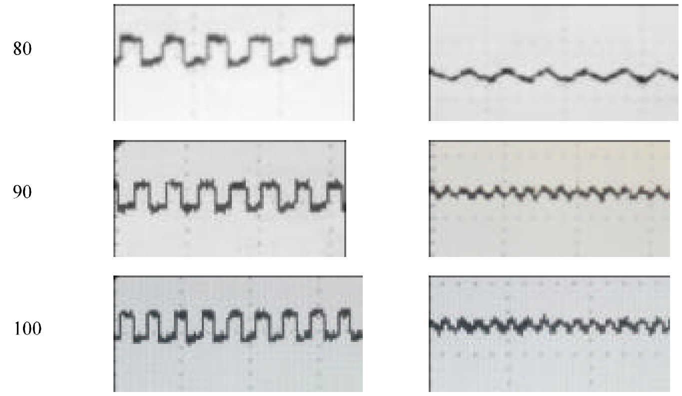

Fig. 12: The comparison of input and output signal as the frequency being increased up to 100 kHz

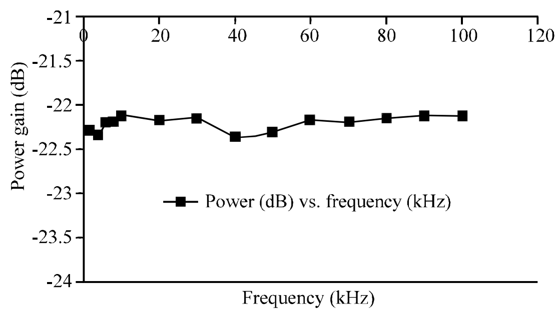

Fig. 13: The graph of power (dB) vs. frequency (kHz) in the range from 1 kHz up to 100 kHz

frequency. As the frequency being increased, the rectangular waveform was distorted becoming a triangular waveform. In this study, the power received from the variable frequencies was analysed. The 1st experiment was completed by varying the frequency of the input signal. As shown in Fig. 13, the trend of the output power fluctuated as the frequency increased in the range of 1-100 kHz. The value of the power in Fig. 13 was defined in terms of decibels. The voltage supplied for the LED was designed to be 3.2 V; however from the oscilloscope reading, it was shown the voltage value varied from 3.09-3.11 V. The output voltage was calculated in decibels using the equation of Power Gain, $G = 20 \log (V1/V2)$. Though the expected results were obtained the received voltage level was in millivolts which was considered very low. Therefore, the efficiency of the photocell as the receiver was too low.

At low frequencies, the LEDs were seen flickering which disturbed the signal transmission. As a result, the output audio was not clear because of the disturbance. For high frequencies, the flicker was too fast to be distinguished by the human eye and the LED appeared to be consistently illuminated.

CONCLUSION

From these experiments, the characteristics of the optical waves were identified. The experiments led to the conclusion that LED light could be applied to communications with further advancement in the transmittance and receiver. From this research, the output of audio signals could still be heard, even at the distance of 50 cm.

The ability to get the clear output signal relied not only on the LED but also on the amplifier and signal restorer. The good amplifier and signal restorer were able to contribute to the efficiency of the visible light communication system. The 2nd experiment identified the effects of frequency on the output power (dB). Based on the results, the increase in frequency did not greatly effect the output power. The fluctuating output power value could be caused by the effect of the luminance from the sorroundings. The difference in the shape of the output and input waveform was related to the increment of the frequency. At low frequencies, the photodetector was nearly ideal in terms of linearity and reponsivity but it was not useful because of limited reponsivity and limited optical power density. More research on the visible light communication needs to be done so that an implementation of this communication system can be a turned into a reality.

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