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Abstract. Traditional visible light communication (VLC) uses positive-intrinsic-negative photodiode (PD) or avalanche PD as the optical receivers (Rx). We demonstrate using a solar cell as the VLC Rx. The solar cell is flexible and low cost and converts the optical signal into an electrical signal directly without the need of external power supply. In addition to acting as the VLC passive Rx, the converted electrical signal from the solar cell can charge up the battery of the Rx nodes. Hence, the proposed scheme can be a promising candidate for the future Internet of Things network. However, a solar cell acting as a VLC Rx is very challenging, since the response of the solar cell is limited. Here, we propose and demonstrate using predistortion to significantly enhance the solar cell Rx response for the first time up to the authors' knowledge. Experimental results show that the response of the solar cell Rx is significantly enhanced; and the original 2-kHz detection bandwidth of the solar cell can be enhanced by 250 times for receiving 500-kbit/s VLC signal at a transmission distance of 1 m. The operation principle, the generated voltage by the solar cell, and the maximum data rates achieved at different transmission distances are also studied. [DOI: 10.1117/1.OE.55.1.010501]

Keywords: optical communications; visible light communication; optical wireless communication; passive optical receiver.

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1 Introduction

Visible light communication (VLC)[1–7] has attracted much attention recently due to free license and electromagnetic interference; hence, people believe that it can be suitable to be deployed in radio-frequency (RF)-prohibited areas, such as airplanes, hospitals, and power plants. In addition, VLC is very directional and uses the visible spectrum of the electromagnetic wave other than the very overcrowded conventional RF spectrum; hence, it is believed that VLC can be a promising candidate to provide high-density and high-capacity wireless communications required for the future fifth generation (5G) wireless networks.[8] Recently, 4 Gbit/s data rate VLC transmission using red–green–blue (RGB) lasers has been demonstrated.[9] In addition, the Internet of Things (IoT) network is becoming more and more popular and many devices are connected for sensing or resource sharing. VLC could also play an important role in the future IoT.[10]

Traditional VLC systems reported in the literatures use positive-intrinsic-negative (PIN) photodiode (PD) or avalanche PD (APD) as the optical receivers (Rxs). However, both types of PDs require external biasing power to operate. In addition, APD needs very high bias voltage to produce the avalanche process inside the APD.

In this work, we demonstrate using solar cell as the Rx for VLC and propose using signal predistortion to increase the response of solar cell Rx. The solar cell is flexible, low cost, and can be manufactured into different shapes. The solar cell converts the optical signal into electrical signal directly without the need of external power supply; hence, it can lower the deployment cost of the VLC. In addition to acting as the VLC passive Rx, the converted electrical signal from the solar cell can charge up the battery of the Rx nodes. Hence, the proposed scheme can be a promising candidate for the future IoT network. However, solar cell acting as VLC Rx is very challenging, since the response of the solar cell is very limited. Wang et al.[11] propose using spectral efficiency orthogonal frequency division multiplexing (OFDM) signal to enhance the data rate of the solar cell Rx-based VLC channel. However, OFDM requires complicated modulation/demodulation processing as well as high speed digital-to-analog converter (DAC) and analog-to-digital converter (ADC) at the transmitter (Tx) and Rx sides. In addition, OFDM signal has a noise-like amplitude with a large peak-to-average power ratio; therefore, it requires Rx with a large dynamic range to avoid signal clipping. Here, we propose and demonstrate using predistortion to significantly enhance the solar cell Rx response. As the signal is on-off keying (OOK) based, very simple generation and detection circuits are needed. We will first describe the operation principle of the predistortion and measure the 3-dB detection bandwidth of the solar cell. Experimental results show that the response of the solar cell Rx is significantly enhanced; and the original 2-kHz detection bandwidth of the solar cell can be enhanced for receiving 500 kbit/s VLC signal at a wireless transmission distance of 1 m and the bit error rate (BER) satisfying the forward error correction (FEC) threshold.

2 Experiment

Figure 1 shows the experimental setup of using the passive solar cell Rx for the VLC. First, the pseudorandom binary sequence OOK signal generated by MATLAB® program is transferred to an arbitrary waveform generator (Tektronix AFG3252C), which acts as the DAC to drive a single commercial available white-light light-emitting diode (LED) with a driving voltage of 5 V peak-to-peak. The white-light LED acts as the Tx for the VLC. Then, a predistortion

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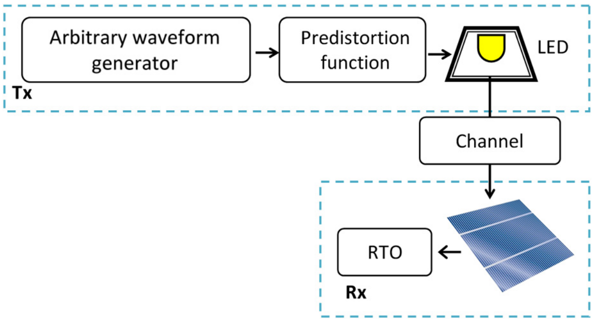

Fig. 1 Proposed experimental setup of using solar cell Rx for VLC. LED, light-emitting diode and RTO, real-time oscilloscope.

function generated by the MATLAB® program is used to produce the predistortion signal. The white-light signal is transmitted through different free-space distances, and received by the solar cell (SC-9728, V_{op}/I_{op}: 6 V/15 mA) with dimension of 9.7 cm × 2.8 cm, which is connected to a real-time oscilloscope (RTO) (Tektronix TDS2022B). The converted electrical signal from the solar cell can be used for VLC as well as charging up the battery of the Rx node. The RTO acts as the ADC, and the received VLC signals are analyzed using MATLAB® program.

3 Results and Discussion

Figure 2(a) shows the measured 3-dB detection bandwidth of the solar cell. It is measured by sending different frequency sinusoidal white-light signals from the LED and detected by the solar cell Rx. We can observe that the 3-dB frequency response is about 2 kHz, which is limited by the large capacitance effect in the solar cell. In order to enhance the solar cell Rx response, a predistortion signal is proposed and deployed. In the predistortion scheme as shown in Fig. 2(b), the first half-period of logic "one" is set at the peak value (i.e., 100%), the amplitude of second half-period is purposely decreased to 78%. For logic "zero," the first half-period is set at 0%, while the amplitude of the second half-period is purposely increased to 76%. We believe that these values of decreasing the second half-period of logic "one" and increasing the second half-period of logic "zero" depends on the actual frequency response of solar cell Rx; and these values can be adjusted if different solar cells are used.

Then we evaluate the BER transmission performances of the proposed VLC system. At the transmission distance of 0.75 m and without using the proposed signal predistortion, no BER measurement can be obtained at a data rate of 10 kbit/s. The inset of Fig. 3(a) shows the highly corrupted eye-diagram of the 10 kbit/s VLC signal detected by the solar cell Rx without using the proposed predistortion scheme. The highly corrupted received eye-diagram is due to the limited frequency response of the solar cell Rx (i.e., 3-dB bandwidth is 2 kHz). Then, the predistortion OOK signal is applied; and the measured BER performances at different data rates and different transmission distances are shown in Fig. 3(a). The experimental results show that the VLC data rate of 500 kbit/s at FEC threshold under wireless transmission distance of 1 m can be achieved. Also, the data rate of 350 kbit/s at BER of 10^{-9} under wireless transmission

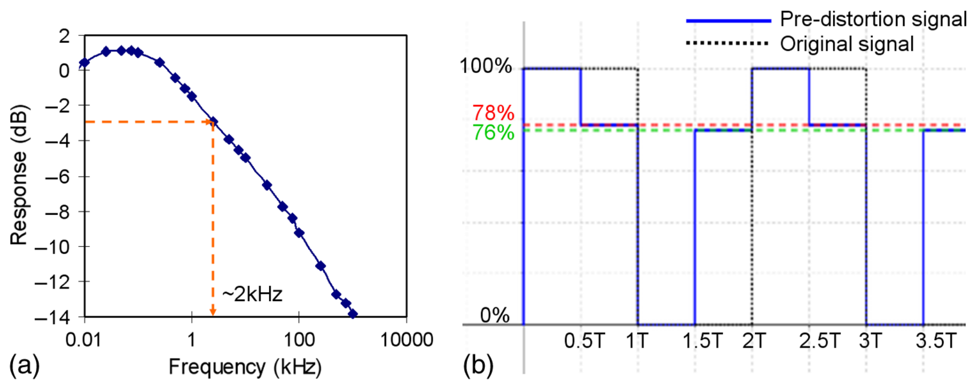

Fig. 2 (a) Measured 3-dB detection bandwidth of the solar cell and (b) the predistortion scheme used.

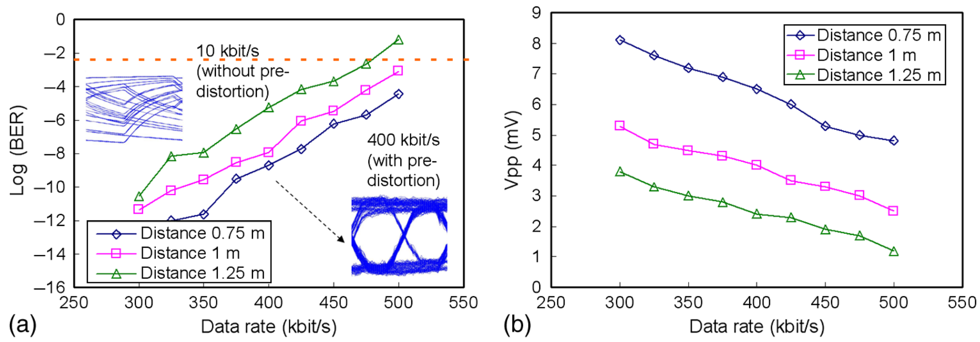

Fig. 3 (a) BER measurements at different data rates and transmission distances, and (b) voltage generated by solar cell Rx at different data rates and distances.

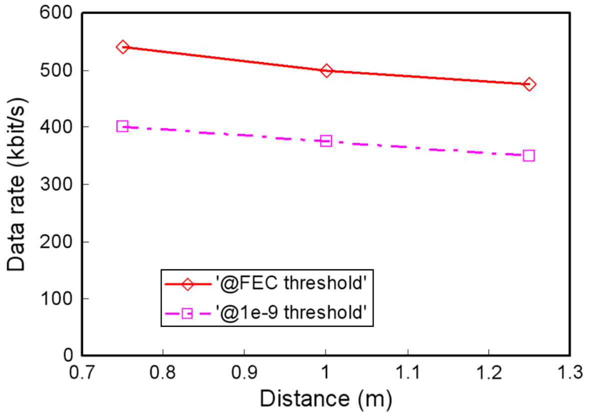

Fig. 4 Maximum data rates achieved under different wireless transmission distances at FEC and 10^{-9} thresholds.

distance of 1.25 m can be observed. The measured eye-diagram of deploying predistortion scheme (operated at 400 kbit/s) is included in inset of Fig. 3(b), revealing that the eye-diagram is widely opened.

Furthermore, we also analyze the voltage generated by the solar cell Rx at different data rates and different transmission distances, as shown in Fig. 3(b). When the data rate or the wireless transmission is decreased, the voltage generated by the solar cell can be increased. Finally, Fig. 4 shows the maximum data rates achieved under different wireless transmission distances at FEC and 10^{-9} thresholds; we can observe that data rates of 500 and 375 kbit/s can be achieved at FEC and 10^{-9} thresholds, respectively, at the transmission distance of 1 m. The maximum transmission distance of the system depends on the optical signal-to-noise ratio received by the solar cell and data rate. Transmission above 2 m is possible when the data rate is >100 kbit/s. All these results show that the predistortion scheme can significantly enhance the response of the solar cell Rx.

4 Conclusion

Traditional VLC systems reported in the literatures used PIN PD or APD as the optical Rxs. However, both types of PDs required external biasing power to operate. In this work, we demonstrated using solar cell as the Rx for VLC. The solar cell was flexible, low cost, and can be manufactured into different shapes. It can act as the passive Rx for VLC as well as charging up the battery of the Rx nodes; hence, it can be a promising candidate for the future IoT network. Previous scheme using solar cell as VLC Rx had limitations. Here, we proposed and demonstrated using predistortion to significantly enhance the solar cell Rx response. As the signal is still OOK based, very simple generation and detection circuits were needed. We described the operation principle of the predistortion and measured the 3-dB detection bandwidth of the solar cell. Experimental results showed that the response of the solar cell Rx was significantly enhanced; and the original 2-kHz detection bandwidth of the solar cell can be enhanced by 250 times for receiving 500 kbit/s VLC signal at a wireless transmission distance of 1 m, satisfying the FEC threshold. We can observe that data rates of 500 and 375 kbit/s can be achieved at FEC and 10^{-9} thresholds, respectively, at the transmission distance of 1 m.

Acknowledgments

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