Photovoltaic Devices Design Based on Simultaneous Visible-Light Information and Power Transfer Circuits

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Abstract. In the Internet of Things (IoT) applications based on visible light communication (VLC) systems, such as outdoor intelligent transportation and indoor intelligent home, a large amount of light energy is scattered. Therefore, this paper studies a visible light receiving circuit based on VLC, which is used to collect energy and receive data at the same time to solve such problems, which is called the simultaneous visible-light information and power transfer (SVIPT) circuit. At present, most of the circuits with similar functions to SVIPT are based on two branches, where they are using capacitors to filter direct current (DC) in the data reception branch and inductors to block alternating current (AC) signals at the energy collection end, but these circuits are inefficient and have significant drawbacks that cannot be truly used in practical applications. The SVIPT circuits proposed in this paper discard the previous concept and we have analyzed the main functions of the two branches specifically. Finally, the SVIPT circuit architecture that can be used in the actual scene is designed, and some simulations are carried out to prove its feasibility.

Keywords: Photovoltaic devices · simultaneous visible-light information and power transfer (SVIPT) · energy harvesting · visible light communication (VLC) · receiving circuit

1 Introduction

Today, the Internet of Things (IoT) is becoming more and more common in our daily lives. Home appliances, furniture, wearables and outdoor intelligent transportation are seamlessly connected to the Internet to exchange information for proper operation, with the ultimate goal of improving our lives by monitoring and controlling the environment around us [1]. The deployment speed of IoT products is very fast, increasing from 9 billion in 2013 to more than 20 billion in 2022, and will continue to increase with the huge market demand. This growth will bring more than 100 billion dollars of opportunities to the healthcare, intelligent home, intelligent transportation, public utilities and consumer electronics markets. To enable true thing-to-thing information transfer, IoT

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devices must have a wireless means of communication, as unconstrained devices can be easily integrated into everyday objects, especially if they can be placed in areas that are inaccessible to people. In addition, IoT devices should be able to harvest energy from their environment to avoid frequent manual charging or regular battery replacement [2], and most of all to save available resources and maximize the energy use of available resources [3].

Visible light communication (VLC) [4] technology is developing rapidly in the world today to generate the Internet of Lights (IoL) scenario, so this technology generally transmits information by switching frequencies that cannot be detected by human eyes, and will not interfere with the normal operation of other equipment [5]. If VLC is used for information exchange between things, it is possible to use light for both data transmission and lighting [6]. The most important thing is that this kind of IoT communication can complete information transmission at some low transmission rates [7]. The general VLC system is not only vulnerable to the impact of the external environment light, but most of the light emitted by the system will be scattered, resulting in a waste of resources. IoT devices equipped with photovoltaic-type devices [8] can not only collect light energy from LED lights and the external environment, but also receive optically encoded information, and the external ambient light has less influence on the signal reception of photovoltaic devices [9]. In VLC based on photovoltaic devices, energy collection and data reception are carried out simultaneously. At the same time, for intelligent transportation systems similar to VLC, when outdoor sunlight and LED signal light sources overlap, the response rate of photovoltaic devices remains good [10]. Under the same outdoor environmental conditions, the bit error rate of photovoltaic devices is lower than that of photodiodes (PIN) and avalanche diodes (APD) detectors, and when conducting VLC outdoors, photovoltaic devices will generate more electrical energy for storage or power supply to subsequent circuits.

At present, the dual receiving circuits of photovoltaic devices based on VLC are mostly based on two model branches, one for data reception and the other for energy collection [11]. Capacitors are used in the data reception branch to block direct current (DC), and choke inductors are used in the energy harvesting branch to filter out useful signals and let DC signals pass through. However, a disadvantage of this method is that it requires a very large choke inductor and a relatively large space footprint. The resistance is used to simulate the energy collection load. Although the resistance provides a good first-order load approximation for energy collection, it cannot capture high-order effects, and the resistance cannot collect energy. The most important thing is that the voltage at both ends of the photovoltaic devices is very unstable, and it is easy to be affected by light, which will have a certain impact on the subsequent energy storage. This model branch has obvious disadvantages and cannot be used directly in VLC. To further solve the existing defects, this paper relates to a kind of circuit of simultaneous visible-light information and power transfer (SVIPT) based on energy collection and data reception of photovoltaic devices [12], and it is mainly used to save resources by collecting the remaining light energy when the VLC is carried out and absorbing the external ambient light when the VLC is not carried out [13]. The main advantage of the designed circuit is the materialization of the two branches. In the energy collection branch, a boost circuit is used to stabilize the voltage rise at both ends of the photovoltaic devices at a certain value, and then it is transported to the supercapacitor for energy storage and power supply to the amplifier in signal transmission. In the data receiving branch, a current sensing resistor is used to sense the useful signal and transport the subsequent processing circuit, which systematically solves the practicability of the energy collection and data receiving circuit based on VLC.

2 Principle of Photovoltaic Devices Model

Compared with PIN tubes and APD tubes, photovoltaic devices are increasingly used in VLC systems, which do not require external bias and rely on their built-in electric field for signal transmission, and generate excess power while doing so. Even though the large capacitance of the photovoltaic devices will directly lead to the response speed of the device itself, the large receiving area of the photovoltaic devices makes it have a stronger light capture capability. In addition, the main thing is that IoT based on VLC does not need a high-speed transmission rate like intelligent homes and general photovoltaic devices can meet its communication needs.

2.1 Photovoltaic Devices Model for Energy Harvesting

Most of the commercially available photovoltaic devices are PN junction structures, so when the photovoltaic devices are used as an energy harvesting device its equivalent circuit is shown in Fig. 1, with R_L denoting the load. The DC model of photovoltaic devices can be seen as consisting of a constant current source, a diode, a compound resistor and a series resistor. According to the equivalent model, the relationship between the output current and voltage of the photovoltaic devices can be derived as [14]:

$$I_{pv} = I_{ph} - I_d - \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \tag{1}$$

where I_{pv} and V_{pv} are the output current and output voltage of the photovoltaic devices, I_{ph} is the constant current source current, R_s is the series resistor, and R_{sh} is the compound resistor. I_d is the diode forward current, the value of which can be calculated by the following equation:

$$I_d = I_0 \exp[\frac{q(V_{pv} + I_{pv}R_s)}{NAkT} - 1] \tag{2}$$

where I_0 denotes the reverse saturation current of the diode, q is the charge of an electron, N is the number of photovoltaic devices in series, A is the diode ideal factor, k is the Boltzmann constant, and T is the Kelvin temperature.

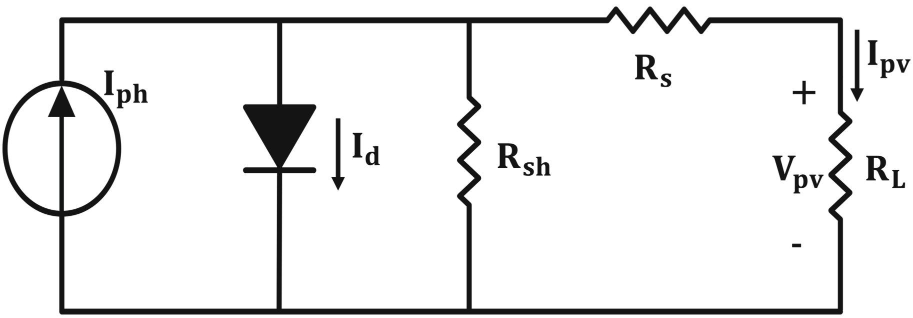

Fig. 1. Photovoltaic devices model for energy harvesting.

2.2 Photovoltaic Devices Model for Communication Systems

When photovoltaic devices are used for information transmission, their alternating current (AC) equivalent model is shown in Fig. 2. For photovoltaic devices, large internal capacitance cannot be ignored, so a capacitor C_S and a parallel resistance R_{sh} are used to equivalent the internal capacitance effect of photovoltaic devices. A small signal equivalent resistance r is used to replace the diode, and a series inductor L is added to simulate the inductance at the connection of the photovoltaic devices, and capacitor C is used to block the DC signal to let the AC signal with information pass through. From the above description, it is clear that the frequency response of the photovoltaic devices used for communication systems is given by the following equation [15]:

$$\left|\frac{V(\omega)}{I_{ph}(\omega)}\right|^2 = \left|\frac{\frac{R_L}{R_X}}{\frac{1}{r} + j\omega C_S + \frac{1}{R_{sh}} + \frac{1}{R_X}}\right|^2 \tag{3}$$

where ω is the angular frequency, and j is an imaginary number. R_X denotes the total resistance value of R_s, inductor L, capacitor C_0 and load R_L, whose expression is:

$$R_X = R_s + j\omega L + \frac{1}{j\omega C_0} + R_L \tag{4}$$

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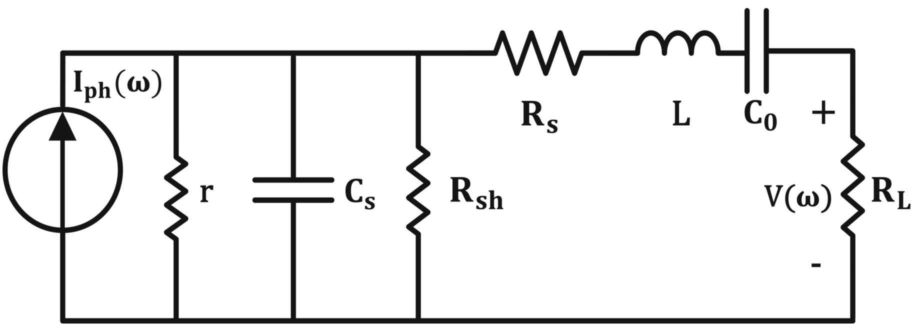

Fig. 2. Photovoltaic devices model for communication.

2.3 Photovoltaic Devices Model for Simultaneous Visible-Light Information and Power Transfer Systems

Nowadays, most people propose a circuit for simultaneous communication and energy collection based on photovoltaic devices to simultaneously collect energy and receive data, as shown in Fig. 3. For this circuit, on the one hand, an inductor L_0 is used in the energy harvesting branch to isolate the AC signal to stop ripple noise, and R_L is used instead of the energy harvesting part. On the other hand, a capacitor C_0 is used to block DC for data reception, and the voltage signal across R_c is used as the signal transmission part. The photogenerated current is generally composed of two components, a DC component I_{ph} for energy harvesting and an AC component $I_{ph}(\omega)$.

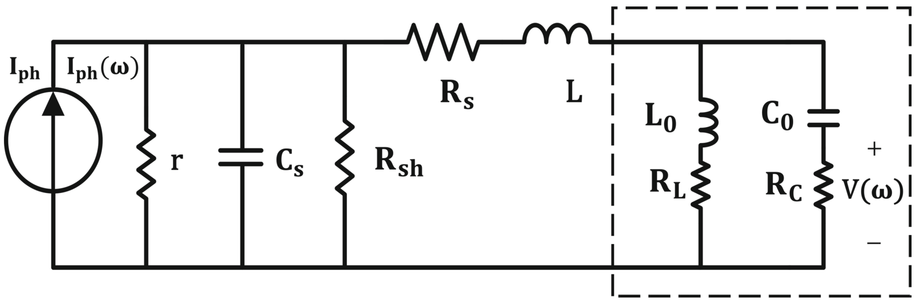

Fig. 3. Photovoltaic devices model for SVIPT circuits.

for signal transmission action. The frequency response of its entire structure can be calculated by the following equation [16]:

$$\left|\frac{V(\omega)}{I_{ph}(\omega)}\right|^2 = \left|\frac{\frac{R_{LC}}{R_s+j\omega L+R_{LC}} * \frac{R_C}{1/j\omega C_0+R_C}}{\frac{1}{r}+\frac{1}{1/j\omega C_s}+\frac{1}{R_{sh}}+\frac{1}{R_s+j\omega L+R_{LC}}}\right|^2 \quad (5)$$

R_{LC} represents the sum of the parallel network resistances of the two branches for energy collection and data reception, which is expressed as:

$$R_{LC} = \frac{1}{\frac{1}{j\omega L_0+R_L}+\frac{1}{1/j\omega C_0+R_C}} \quad (6)$$

Although energy collection and data reception can be carried out at the same time, this method is extremely vulnerable to external noise interference and requires a large space. The most important thing is that the energy collection voltage is unstable and energy storage cannot be carried out effectively.

3 Design of SVIPT Circuits

This paper focuses on the design of a SVIPT circuit for energy harvesting and data reception based on photovoltaic devices. As shown in Fig. 4, the overall schematic diagram of this circuit structure is placed on the whole visible light system. On the one hand, at the transmitter side, the encoded signal is superimposed with the LED drive signal to control the bright and dark changes of the LED, which does not affect the lighting because the signal transmission rate is so fast that the human eye cannot discern the changes in the brightness of the LED. On the other hand, at the receiving end, the photovoltaic devices receive the signal from the LED and the external ambient light, and the photocurrent generated is partly converted into the voltage at both ends by the current sensing resistor, and partly stored in the supercapacitor through the boost circuit for subsequent power supply to the receiving chip.

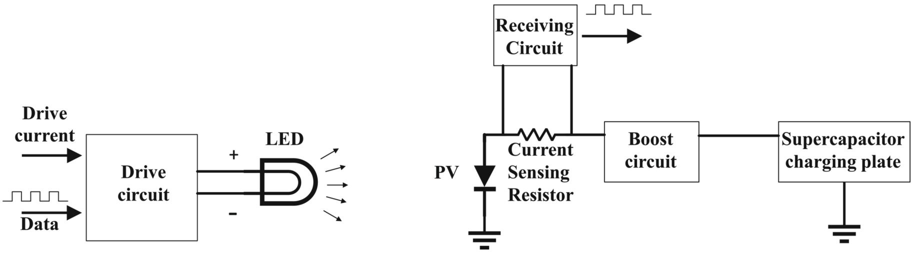

Fig. 4. Diagram of the entire VLC structure using the SVIPT circuit.

This circuit mainly consists of modules such as photovoltaic type devices, a current sensing resistor, boost circuits, a supercapacitor charging board, instrument amplifier circuits, bandpass filter circuits, comparison circuits and reference level circuits [17], etc. And the specific circuit is shown in Fig. 5. The current sensing resistor is generally very small, about a few ohms, and its main role is to convert the current signal into a voltage signal across the current sense resistor and then transmitted it to the instrument amplifier circuit. The instrument amplifier circuit is mainly used to convert the voltage signals at both ends of the current induction resistance into unidirectional signals and amplify them in a certain proportion, and the amplification factor is given by the following equation:

$$G = 5 + 5\frac{R5}{R4} \tag{7}$$

The instrument amplifier chip used in this circuit is the INA322 from Texas Instruments, which is suitable for this circuit due to its low power consumption and low price. After the instrument amplifier circuit, the signal is then transmitted to a band-pass filter and compared with the reference circuit to restore the originally transmitted signal, and the main function of the band-pass filter is to filter out the very low frequencies in the signal and the high-frequency noise generated by the external environment and the circuit, retaining only the useful signal. The bandwidth of the bandpass oscilloscope of this circuit is shown in Fig. 6. Respectively, the amplifier chips used in the bandpass filter circuit and the comparison circuit are OPA2340 and TLV7011.

Compared with other energy collection and data-receiving model circuits, this circuit does not use a choke inductor to filter out useful signals on the energy collection branch, nor does it use resistance to simulate the energy collection load. Instead, it uses a low-power boost chip to raise the voltage of the photovoltaic device to a certain value, i.e

3.3 V, so that the voltage can be stabilized before charging the subsequent supercapacitor charging plate. By controlling the resistance values of R2 and R3, the voltage value after boosting can be changed, and the numbers of all chips in this circuit and their performance parameters are shown in Table 1. The charging and discharging circuit of the supercapacitor is simpler than that of the battery, and the supercapacitor is small in size, saving space. What's more, the subsequent supercapacitor can also provide energy for those operational amplifier chips. On the data-receiving branch, instead of blocking the DC signal with a capacitor, the current sensing resistor senses the current change and converts it into the voltage signal at both ends, which is then amplified and filtered by the subsequent circuit to filter out the extremely low-frequency noise, the high-frequency noise of the circuit and the external environment, and then compare them to reduce the bit error rate as much as possible.

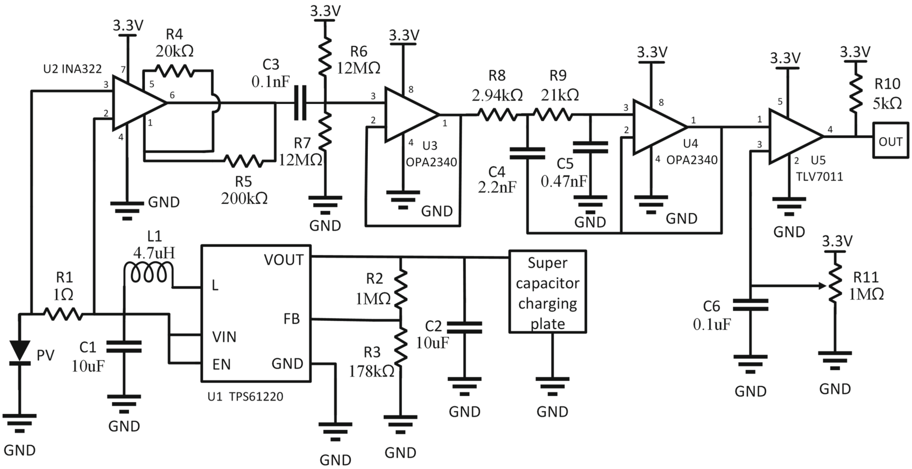

Fig. 5. SVIPT overall circuit diagram.

Table 1. Performance parameters of the chip used.

Chip Number	Chip Name	Supply Voltage	Conversion Efficiency	Voltage Noise (1 kHz)	Quiescent Current
U1	TPS61220		Up to 95%		5.5 uA
U2	INA322	3.3 V		$100\ \text{nV}\sqrt{\text{Hz}}$	40 uA
U3 and U4	OPA2340	3.3 V		$25\ \text{nV}\sqrt{\text{Hz}}$	750 uA
U5	TLV7011	3.3 V		$75\ \text{nV}\sqrt{\text{Hz}}$	5 uA

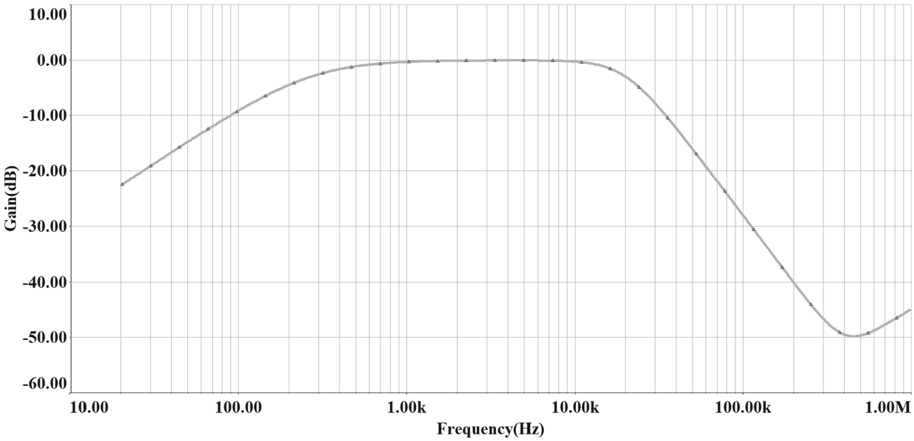

Fig. 6. Bandwidth of this circuit.

4 Results and Discussions

General silicon solar cells have high photoelectric conversion efficiency. When silicon photovoltaic devices are used as visible light detectors in SVIPT circuits, the voltages at both ends of the detectors can be effectively boosted and transmitted encoded digital signals. For example, when transmitting a 1 kHz square wave signal [18], the signal output image is shown in Fig. 7. As can be seen, at the signal output, the 1 kHz square wave signal is converted into a voltage signal after passing through the current sensing resistor and passed to the subsequent circuit for further processing. Although the signal after the bandpass filter is slightly miscoded and distorted, the transmitted square wave signal can be output more completely after adjusting the resistance value of the sliding resistor of the reference level circuit. For the energy harvesting module, adjust the resistance value of R2 and R3 so that the final voltage reaches about 3.3 V, as shown in Fig. 8. Although the output voltage will have some ripple noise, it is within a certain controllable range and will not affect the supercapacitor for energy storage.

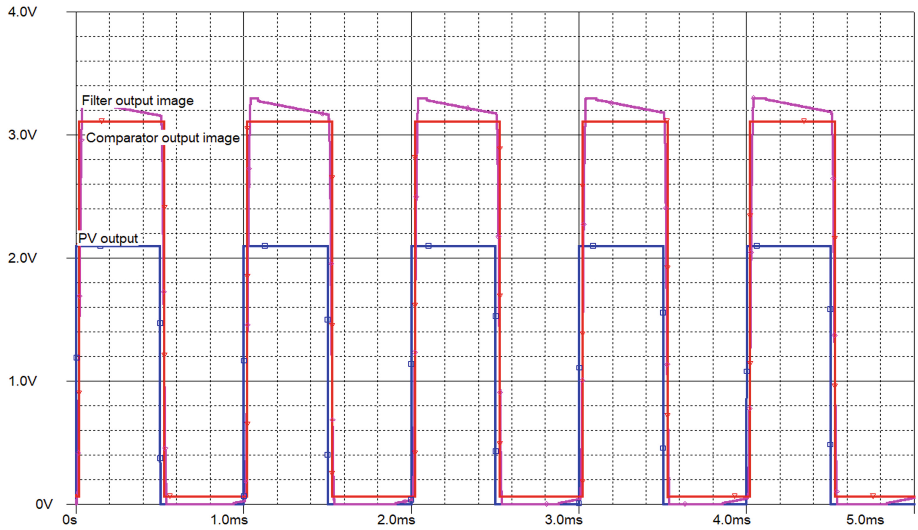

Fig. 7. Output data images for each section.

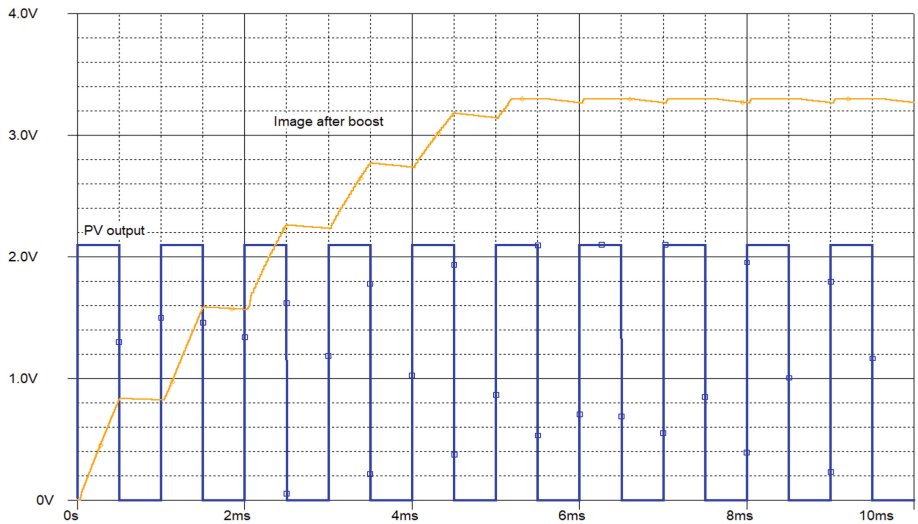

Fig. 8. Boost branch simulation results.

5 Conclusion

To save available resources, we have designed a SVIPT circuit in a VLC system based on photovoltaic devices. In this circuit, for the data transmission branch, we discarded the conventional concept of using a capacitor to filter out the direct flow AC and instead used a current sensing resistor to convert the current signal with information into a voltage signal before transporting it to the back circuit. For the energy harvesting branch, a low-power booster chip is used to boost the photovoltaic device to a certain voltage before powering the supercapacitor. There is a small amount of ripple noise, but it is within the acceptable range. We have simulated this circuit to verify its feasibility, and the circuit takes up little space and can be easily integrated into small VLC systems indoors and outdoors. This circuit can largely reduce the frequency of battery replacement and further reduce the occurrence of emergencies when performing some high-risk work such as underwater communication and inaccessible areas for human beings, so this circuit is of high practical value for VLC in future IoL scenarios.

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