Visible light communication for rapid monitoring of environmental changes using thin film solar cells

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ABSTRACT

This study investigates the use of visible light communication (VLC) for rapid environmental monitoring by leveraging thin film solar cells as signal receivers. VLC, which employs visible light for data transmission, presents an energy-efficient and eco-friendly approach for real-time monitoring. Thin-film solar cells, recognized for their efficiency and low-light performance, function both as environmental sensors and VLC signal receivers. We conducted experiments to evaluate the system's performance across various environmental conditions, such as light intensity and temperature changes. Our findings indicate that thin-film solar cells can swiftly and accurately detect environmental changes while maintaining a low bit error rate for VLC data. The system also shows high responsiveness to rapid light variations, making it well-suited for dynamic monitoring tasks like air quality, humidity, and forest fire detection. This research highlights VLC technology's significant potential for environmental monitoring applications requiring quick, real-time data transmission, and energy efficiency with thin-film solar cells. The integration of this technology promises to enhance environmental monitoring systems, contributing to climate change mitigation and improved environmental management, and sets the stage for developing advanced, sustainable solutions in wireless communication and ecological monitoring.

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1. INTRODUCTION

Rapid and dynamic environmental changes due to climate change, urbanization, and other human activities have become a global concern [1]. Real-time ecological monitoring is critical to anticipate and respond to the negative impacts of these changes [2]. Technology that can detect environmental changes quickly and accurately is needed to support mitigation and adaptation efforts [3]. In this context, the use of visible light communication (VLC) technology offers an innovative and sustainable solution [4]. VLC, which uses the visible light spectrum for data transmission [5], provides an attractive alternative to conventional communications technologies that use radio waves [6]. With a wider spectrum and not affected by strict regulations such as radio frequencies [7], VLC can provide high data capacity and minimal interference [8].

Thin film solar cells are a key component in the integration of VLC technology for environmental monitoring [9]. These solar cells are known for their ability to convert light into electrical energy with high efficiency [10], as well as flexibility in various lighting conditions [11]. Thin-film solar cells not only serve as energy sources but also as VLC signal receivers [12], allowing the system to operate autonomously without requiring a large external power source [13]. This technology offers great opportunities for environmental monitoring applications [14], where systems must operate autonomously in remote and hard-to-reach locations [15]. By utilizing thin-film solar cells [16], environmental monitoring devices can be placed at multiple observation points [17], ensuring broad and continuous monitoring coverage [18]. VLC implementation in environmental monitoring covers various technical and functional aspects [19]. VLC systems must be able to transmit and receive data quickly and reliably [20], even under varying environmental conditions such as changes in light intensity and temperature [21].

This research aims to explore the potential and effectiveness of using VLC with thin film solar cells as signal receivers in the context of environmental monitoring. By carrying out various tests and experiments, this research is expected to provide in-depth insight into system performance in various environmental conditions, as well as identify challenges and opportunities for further development [22]. The findings from this research will make an important contribution to the development of more efficient and environmentally friendly communications and monitoring technologies, supporting global efforts to maintain environmental sustainability and mitigate climate change [23]. This research introduces a novel integration of VLC with thin film solar cells for rapid environmental monitoring, distinguishing itself from existing studies by combining dual functionalities in a single system. Unlike traditional methods, which rely on separate sensors and communication devices, our approach uses thin film solar cells as both environmental sensors and VLC receivers [24]. This dual-role capability enhances system efficiency and reduces energy consumption. Additionally, our study demonstrates how VLC technology can maintain low bit error rates and high responsiveness to rapid light fluctuations, offering a unique solution for real-time, dynamic monitoring of environmental parameters such as air quality and humidity.

2. RESEARCH METHOD

This research uses an experimental approach to examine the effectiveness of VLC in monitoring environmental changes using thin film solar cells as signal receivers. The research process is divided into several main stages, namely system design, laboratory testing, and field testing. At the system design stage, we developed a VLC prototype consisting of an light emitting diode (LED) source as a transmitter and a thin film solar cell as a receiver [25]. This prototype is designed to be able to detect and transmit data on environmental changes in real-time as seen in Figure 1. The thin film solar cells used in this research were selected based on their efficiency in converting light energy into electricity, as well as their ability to function in various lighting conditions. This system is also equipped with a microcontroller which functions to process data received from the solar cells and send it to the control center via a wireless network [26].

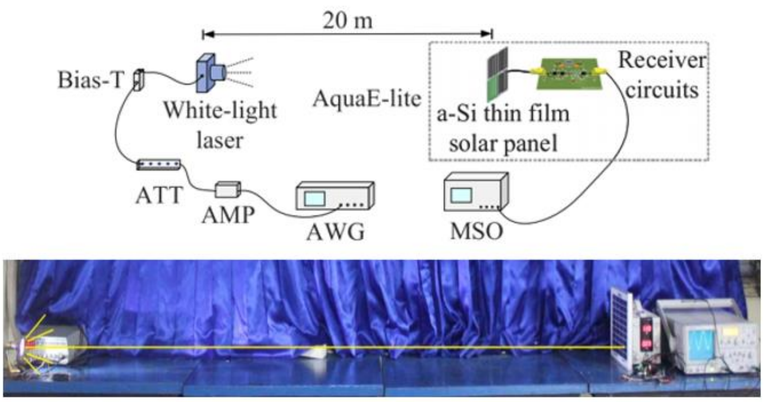

Figure 1. Experiment setup of LED laser and thin film solar panel-based VLC system

In the laboratory testing stage, the prototype is tested in controlled environmental conditions to evaluate system performance in various lighting and temperature scenarios. Trials were carried out with variations in light intensity from low to high conditions, as well as temperature variations to simulate different environmental conditions. Data collected includes bit error rates, the responsiveness of solar cells to changes in light intensity, and the system's ability to detect changes in environmental parameters such as temperature and humidity [27]. The results of this laboratory testing are used to optimize the design and data processing algorithms on the VLC system. Next, the field test stage was carried out to test the system's performance in real conditions. Prototypes are installed in locations selected based on environmental monitoring needs, such as areas with a high risk of rapid ecological change [28]. Data from field tests was analyzed to evaluate the system's effectiveness in detecting and transmitting environmental data in real-time, as well as the system's robustness in various weather and lighting conditions [29]. Through this approach, the research is expected to provide a comprehensive picture of the potential use of VLC and thin-film solar cells in environmental monitoring, as well as identify areas for further technological development.

3. RESULTS AND DISCUSSION

This research examines the use of signal modulation at certain frequencies in a VLC system for rapid environmental monitoring using thin film solar cells as receivers. The use of frequency modulation is key in ensuring stable and accurate data transmission in various lighting conditions and environments. In VLC systems, signal modulation at precise frequencies allows the separation of data from environmental interference and increases transmission reliability. Signal modulation experiments were carried out with various modulation schemes, pulse width modulation (PWM), and frequency shift keying (FSK). Figure 2 shows the results of the PWM test, although simple, it has limitations in varying lighting conditions because changes in light intensity can cause interference in the received signal. PWM, on the other hand, offers the advantage of reducing the impact of light fluctuations by encoding data based on pulse width but is still susceptible to environmental noise [30]. FSK shows the best performance in this test. By encoding data at different frequencies, FSK enables the separation of data signals from environmental noise more effectively. Laboratory testing shows that FSK can maintain a low bit error rate even when light intensity fluctuates. This is due to FSK's ability to modulate data at frequencies that can be easily distinguished by the receiver, namely the thin film solar cells used in this system [31]. Thin-film solar cells show good sensitivity to changes in light signal frequency [32], making them ideal components for the implementation of this modulation scheme [33].

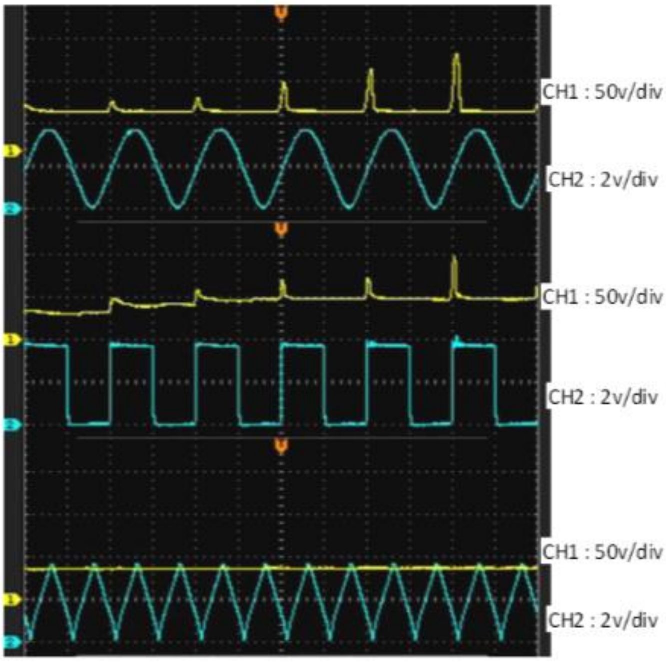

Figure 2. Display of PWM and FSK measurement results

The performance characteristics of thin film solar cells as signal receivers in VLC systems are analyzed through current density versus voltage (J–V) curves. The J–V curve provides important information about the efficiency of light-to-electricity conversion, which is critical for assessing the capabilities of solar cells under varying lighting conditions. The measurement results show that thin film solar cells have high J_{sc} at optimal light intensity, indicating that the material can produce significant current when exposed to light

[34]. The measured V_{oc} also shows good values, reflecting the ability of the solar cells to produce a high voltage under maximum lighting conditions.

The J–V curve in Figure 3 also shows that under low lighting conditions, even though there is a decrease in J_{sc} and V_{oc}, thin film solar cells are still able to produce sufficient power to support VLC system operation. This is important considering that environmental monitoring systems often must function in changing lighting conditions, including at night or during cloudy weather [35]. The reliability of the solar cells under various lighting conditions ensures that the VLC system can operate continuously and stably. Moreover, J–V curve analysis at various light intensities shows that the power conversion efficiency (PCE) of thin-film solar cells remains quite high even at low light intensities. This efficiency allows VLC systems to make optimal use of available light sources, reducing dependence on external power sources [36]. In field tests, the ability of solar cells to maintain good performance in low light conditions proved especially useful for environmental monitoring in areas with heavy cloud cover or in situations where natural lighting is limited [37]. Another factor revealed from the J–V curve is the stability of solar cell performance against temperature variations. Thin-film solar cells show good resistance to temperature changes, with only slight variations in J_{sc} and V_{oc} as the ambient temperature changes. This shows that solar cells can function well in a wide range of climatic conditions, making them reliable components for environmental monitoring systems that must operate in a wide range of weather conditions.

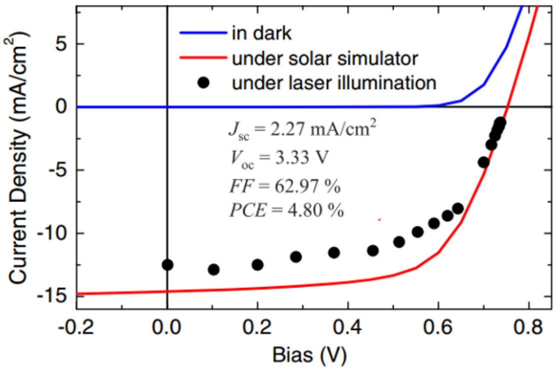

Figure 3. Performance characteristics of thin film solar cells via current density versus voltage (J–V) curves

This research develops a VLC system by utilizing thin film solar cells as signal receivers to monitor environmental changes. The results of laboratory experiments and field tests provide deep insight into the performance and effectiveness of this system under various environmental conditions. In laboratory tests, thin-film solar cells demonstrated excellent capabilities in capturing VLC signals and converting light into electrical signals with high efficiency [38]. At low light intensities, the system continues to operate with minimal bit error rates, confirming that this technology can function well even in less-than-ideal lighting conditions.

Additionally, laboratory testing revealed that the system is highly responsive to changes in light intensity. As the light intensity increases, the signal reception efficiency also increases, resulting in more stable and accurate data transmission [39]. On the other hand, in conditions of very low light intensity, even though there is a slight increase in bit error rate (BER), the data can still be received with an acceptable level of accuracy. This indicates that thin film solar cells are not only effective as energy sources, but also as reliable VLC signal receivers as seen in Figure 4. Temperature variations tested in the laboratory also show that environmental temperature does not have a significant influence on the performance of thin film solar cells in receiving VLC signals, making this system suitable for a variety of environmental conditions including areas with extreme temperatures. Field tests were carried out in several locations with different environmental characteristics, including urban areas with high air pollution, forest areas that are prone to fire, and coastal areas that are vulnerable to extreme weather changes. In urban areas, the system successfully monitors air pollution fluctuations accurately, providing important data for air quality analysis. In forest areas, this system can detect changes in humidity and temperature that could indicate potential forest fires, enabling early preventative action [40]. These results show that VLC systems with thin film solar cells can function well in various environmental conditions and provide accurate and real-time data.

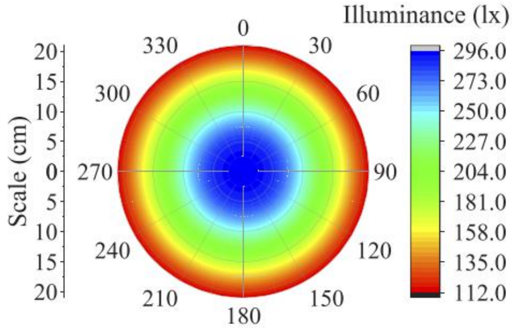

Figure 4. Lighting distribution in the VLC system

In addition, field tests show that the system has good resistance to changing weather conditions. In coastal areas, the system can withstand high humidity and strong winds without experiencing a significant decrease in performance. The ability of thin-film solar cells to function in low-lighting conditions is particularly beneficial for environmental monitoring at night or in areas with thick cloud cover [41]. This is important because many critical environmental events, such as forest fires or increased air pollution, can occur at any time without considering the time of day or lighting conditions. The integration of VLC technology and thin film solar cells also shows advantages in terms of energy efficiency. This system can operate autonomously by utilizing available light energy, reducing dependence on external energy resources [42]. This makes this system ideal for use in remote locations or hard-to-reach areas where electrical resources are limited [43]. Thus, this system not only offers an effective environmental monitoring solution but also contributes to energy sustainability. Besides technical advantages, this research also highlights several challenges that need to be overcome for further development [44]. One of the main challenges is ensuring the consistency and stability of data transmission in highly variable environmental conditions as seen in Figure 5. Although the system demonstrated good performance in laboratory and field tests, further optimization is required to address extreme situations that may not be fully covered in testing [45]. In addition, integration with wider communications networks also needs to be considered to ensure that the data collected can be accessed and analyzed effectively by stakeholders.

Figure 5. Field tests were carried out on the VLC system in several environmental characteristics

The development of more sophisticated data processing algorithms can also increase the capabilities of this system. Better algorithms can help in analyzing data in real time, identifying patterns that indicate significant environmental changes, and providing more accurate early warnings [46]. Thus, this system can become a stronger tool to support mitigation and adaptation actions to environmental changes [47]. The main findings of this study reveal that integrating VLC with thin film solar cells significantly enhances environmental monitoring capabilities. This approach enables rapid and accurate detection of environmental changes while simultaneously serving as an energy-efficient data transmission method. The use of thin film solar cells, which effectively operate under low-light conditions, ensures that the system remains responsive and reliable in diverse environmental settings. The ability to achieve low bit error rates and high responsiveness to light variations underscores VLC's potential for real-time monitoring applications, thereby offering a robust solution for dynamic and sustainable environmental management.

Overall, this research shows that VLC technology using thin-film solar cells as signal receivers has great potential for use in rapid and real-time environmental monitoring. The results of laboratory experiments and field tests show that this system can operate efficiently and accurately in various environmental conditions [48]. The system also shows good resistance to weather and temperature variations, as well as the ability to function in low-lighting conditions [49]. With the integration of this technology, it is hoped that more efficient and sustainable environmental monitoring solutions can be created, supporting global efforts to maintain environmental sustainability and mitigate climate change [50]. These findings pave the way for further development and widespread application of VLC technology in various environmental monitoring applications in the future.

4. CONCLUSION

In summary, this research successfully developed and tested a VLC system that employs thin film solar cells as signal receivers for swift environmental monitoring. Experimental findings demonstrate that thin film solar cells perform effectively under varying lighting conditions, exhibit high PCE, and respond reliably to fluctuations in light intensity and temperature. FSK modulation has proven effective in preserving data transmission quality across different environmental scenarios, ensuring consistent and accurate data delivery. Field trials reveal that the system can detect real-time changes in environmental parameters, providing crucial data for mitigation and adaptation strategies. The energy efficiency of thin film solar cells allows the system to operate independently in remote areas without needing substantial external power sources. Thus, integrating VLC technology with thin film solar cells offers an efficient, reliable, and sustainable solution for environmental monitoring, significantly supporting climate change mitigation and enhanced environmental management.

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