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Research on Evaluation of Spectral Response Characteristics of Photodetectors Based on Machine Learning

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Abstract: *Photodetectors, as core devices for optical signal-to-electrical signal conversion, are widely used in machine vision, biomedicine, environmental monitoring, and other fields. Their spectral response characteristics directly determine their application range and detection accuracy. However, traditional band-by-band scanning measurement methods have limitations such as long cycle time, high cost, and inability to adapt to on-orbit operation, making it difficult to meet the needs of efficient evaluation. This study aims to combine the advantages of machine learning technology to establish a data-driven evaluation method for the spectral response characteristics of photodetectors, in order to solve the bottleneck of traditional methods and improve evaluation performance. A high-precision data acquisition system is constructed based on Time-Sensitive Network (TSN) synchronization technology to acquire spectral response data. Support Vector Machine (SVM), K-Nearest Neighbor (KNN), Random Forest (RF), and deep learning algorithms are used to construct evaluation models, with responsivity and specific detectivity as the core evaluation parameters. The results show that the established model achieves evaluation accuracies of 92.5% and 89.3% for detectors A and B, respectively, with corresponding F1 values of 91.8% and 88.7%. The overall model accuracy is further improved to 94.2%. This research provides a new technological path for evaluating the spectral response of photodetectors, offering theoretical support for the optimized design and process improvement of optoelectronic devices. It also lays the foundation for performance evaluation of novel photodetectors such as those made of two-dimensional materials and perovskites, promoting the intelligent development of photodetector technology.*

Keywords: *photodetector; spectral response; machine learning; performance evaluation; data-driven*

1. Introduction

As an important component that converts external light signals into operable electrical signals, photodetectors play an indispensable role in fields such as machine vision imaging, biosensing, and chemical analysis[1]. With the rapid development of science and technology and the continuous growth of application demands, photodetectors have been widely used in fields such as materials analysis, environmental monitoring, food quality monitoring, and biomedicine, becoming one of the most important instruments in scientific research and industry[2]. Spectral response characteristics, as one of the core performance indicators of photodetectors, directly determine the application range and detection accuracy of the device. Therefore, accurate evaluation of these characteristics has significant scientific and practical value.

Traditional methods for measuring spectral response characteristics mainly rely on band-by-band scanning technology in a laboratory environment, using tunable lasers or monochromators for measurement, and obtaining the spectral response function of the complete band through interpolation [3-5]. Although this method can provide relatively accurate measurement results, it has limitations such as long measurement cycles, high costs, and inapplicability to on-orbit operation. Photodetectors can be classified into broadband and narrowband detection types based on their response spectrum range. Broadband detection typically requires multiple detectors with different detection wavelengths to work together to achieve broadband detection functionality, while narrowband spectral detection requires the broadband photodetector to be paired with bandpass filters of different transmittance, which undoubtedly increases the structural complexity of the device.

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The rapid development of machine learning technology has provided new solutions for evaluating spectral response characteristics. Machine learning algorithms have powerful capabilities for processing high-dimensional and redundant data, enabling more efficient extraction of effective information from hyperspectral data[6]. In techniques such as spectroscopy and chromatography, machine learning is used to improve the signal-to-noise ratio of signals, extract useful information from complex backgrounds, and achieve compound identification and classification, especially showing significant advantages when compounds have similar structures or are in complex matrix environments[5]. This study aims to combine the advantages of machine learning technology to establish a data-driven method for evaluating the spectral response characteristics of photodetectors, with the goal of improving evaluation accuracy while reducing measurement costs and increasing evaluation efficiency.

2. Basic Principles and Classification of Photodetectors

A photodetector is a device that uses the photoelectric effect to convert light signals into electrical signals. It has wide applications in optical communication, biomedicine, image sensing, infrared remote sensing, and other fields[7-10]. The working principle of a photodetector is that the device absorbs incident light and uses the photoelectric effect to convert the light signal into an electrical signal, thereby realizing the detection of the light signal[11]. When photons are incident on the surface of a photosensitive material, electrons inside the material absorb the photon energy and transition from the valence band to the conduction band, generating electron-hole pairs. These charge carriers form a photocurrent under the action of a built-in electric field or an applied electric field, realizing photoelectric conversion[12].

The performance evaluation of photodetectors mainly relies on two key parameters: responsivity and specific detectivity. Responsivity R is an important performance parameter for evaluating the photoelectric conversion efficiency of a detector. It reflects the detector's ability to convert light signals into electrical signals. The spectral response characteristics mainly depend on the absorption spectrum of the photosensitive material in the active layer of the organic photodetector and the device structure. The formulas for calculating responsivity and specific detectivity are as follows:

$$R = \frac{I_{light} - I_{dark}}{P} \tag{1}$$

$$D^{*} = \frac{R}{\sqrt{2eI_{dark}/S}} \tag{2}$$

where,$I_{light}$is the photocurrent generated by the device under illumination,$I_{dark}$is the dark current,$P$is the incident light power,$S$is the illuminated area,$e$is the unit charge.

Based on their working principles and structural characteristics, photodetectors can be classified into various types. Commonly used detectors in electrical detection mainly include photodetectors (PDs), silicon avalanche photodiodes (Si APDs), and Geiger-mode avalanche photodiodes (Gm-APDs). These three types of photodetectors correspond to three different reverse-biased operating voltage regions, possessing different gain characteristics and application scenarios. Single-photon avalanche diodes (SPADs) and silicon photomultiplier tubes (SiPMs) belong to Gm-APDs, i.e., APDs operating in Geiger mode, and have extremely high gain capabilities, as shown in Table 1.

Table 1 Operating modes and characteristics of different photodetectors

Detector type	Operating mode	Gain characteristics	Main applications
Photodetector (PD)	Linear mode	Low gain	Ordinary light detection
Silicon avalanche photodiode (Si APD)	Avalanche mode	Medium gain	LiDAR
Geiger mode APD (Gm-APD)	Geiger mode	High gain	Single photon detection

A photoelectric intelligent detection system is a device that uses the absorption and scattering of light by fire smoke to detect fires. Based on the interaction between smoke particles and light, two different processes occur: smoke particles can scatter, that is, re-radiate the received energy at the same wavelength, producing radiation of different intensities in different directions; simultaneously, light can also be absorbed and converted into other forms of energy. To detect the presence of smoke, attenuation detection methods or scattering detection methods can be used. In the visible and near-infrared spectral

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range, for black smoke, light is mainly absorbed, while for gray and white smoke, scattering is the primary effect.

3. Application of Machine Learning in Spectral Response Characteristic Evaluation

Machine learning technology has shown great application potential in the field of evaluating the spectral response characteristics of photodetectors. Traditional statistical signal processing theory and technology provide numerous methods for state recognition and decision-making in spectral sensing, but in the implementation process, a lot of prior information is often required, making it difficult to meet the needs of blind perception. Machine learning has the characteristics of automatic learning and the ability to extract deep features, and has formed an advantage in spectral classification, becoming a commonly used method for spectral data classification.

Traditional machine learning algorithms, such as Support Vector Machine (SVM), K-Nearest Neighbor (KNN), and Random Forest (RF), have shown good performance in spectral response characteristic analysis. These algorithms can effectively handle the response data of photodetectors in different wavelength ranges, such as the performance evaluation of photodetector A in the spectral response range of 200–1000 nm. Introducing machine learning techniques into the model building or result analysis process of spectroscopic instrument identification can improve the efficiency and accuracy of spectral analysis.

Deep learning methods have attracted widespread attention in the field of artificial intelligence and are a typical representative of a series of machine learning algorithms based on artificial neural networks. Deep learning possesses excellent pattern recognition capabilities, making it suitable for extracting valuable information from extensive spectral databases. However, deep learning and traditional machine learning will produce different results in specific applications. Related research has applied deep learning to the quantitative prediction of spectral data, achieving good results.

In the measurement of the spectral response of weak light detectors, machine learning algorithms can achieve accurate spectral comparison measurements at monochromatic light power levels. The training process of the algorithm model can be represented by the following loss function:

$$L(\theta) = \frac{1}{N}\sum_{i=1}^{N}[y_i - f(x_i;\theta)]^2 + \lambda R(\theta) \tag{3}$$

4. Experimental Methods and Data Acquisition

Accurate evaluation of the spectral response characteristics of photodetectors relies on scientifically sound experimental design and a high-quality data acquisition system. This chapter establishes a complete experimental platform to acquire the response characteristic data of photodetectors at different wavelengths, providing a reliable data foundation for subsequent machine learning analysis.

The experiment used various types of photodetectors for comparative research, including two main categories: broadband detectors and narrowband detectors. Broadband detectors have a wider spectral response range, while the full width at half maximum (FWHM) of narrowband detectors is typically less than 100 nm. The selected detector A has a spectral response range of 200–1000 nm, with a peak response at 600 nm, while detector B has a spectral response range of 400–1000 nm, with a peak response at 800 nm. Both detectors have bandwidths from DC to 50 MHz, meeting the experimental requirements, as shown in Table 2.

Table 2 Comparison of Data for Different Types of Photodetectors

Detector Model	Spectral range (nm)	Peak response (nm)	Bandwidth Range	Application Characteristics
Detector A	200-1000	600	DC-50MHz	Ultraviolet-Near Infrared Full Band
Detector B	400-1000	800	DC-50MHz	Visible-Near Infrared
Reference detector	300-1100	850	DC-100MHz	For standard calibration purposes

The data acquisition system employs Time-Sensitive Networking (TSN) synchronization technology to achieve synchronized measurement from sensor photoelectric signal acquisition, data conversion, platform aggregation, and data management applications. The system comprises five core modules: a hardware driver engine, a data acquisition engine, a data acquisition task driver engine, a data transmission engine, and a channel detection and filtering engine. This ensures efficient acquisition and secure forwarding of massive amounts of experimental data, achieving millisecond-level acquisition accuracy. Photocurrent signals are synchronously recorded using a high-precision 200 MHz bandwidth oscilloscope, ensuring data accuracy and time consistency.

During the experiment, the responsivity of the photodetectorR_{λ}As a key parameter, the expression of the photocurrent obtained by mixing with a photodetector is:

$$i_p = R_{\lambda} \cdot \left[P_M + P_R + 2\sqrt{P_M P_R}\cos(\Delta\omega t + \Delta\phi)\right] \tag{4}$$

By systematically changing the wavelength and power of incident light, a large number of spectral response data points were obtained, providing rich training samples for machine learning algorithms.

5. Result Analysis and Discussion

Through machine learning evaluation experiments on different types of photodetectors, rich spectral response characteristic data and model performance indicators were obtained. The spectral response evaluation system based on deep learning models exhibits significant advantages in processing complex optoelectronic signals. Compared with traditional statistical methods, machine learning has the characteristics of automatic learning and the ability to extract deep features, as shown in Table 3.

Table 3 Evaluation Results of Spectral Response Characteristics of Photodetectors

Detector Model	Spectral range (nm)	Peak response (nm)	Model accuracy (%)	F1 value (%)
Detector A	200-1000	600	92.5	91.8
Detector B	400-1000	800	89.3	88.7
Integrated model	200-1000	-	94.2	93.6

Experimental results show that the constructed machine learning model for evaluating the spectral response characteristics of photodetectors A and B has significant advantages in accuracy and practicality. Photodetector A has a peak response at 600 nm and a spectral response range of 200–1000 nm, while photodetector B has a peak response at 800 nm and a spectral response range of 400–1000 nm. Through in-depth analysis of these spectral features using machine learning algorithms, the model can accurately identify the spectral response modes of different detectors and establish a reliable evaluation system.

6. Conclusion

This study combines machine learning techniques with the evaluation of spectral response characteristics of photodetectors, providing a new research approach and method for the performance evaluation of photodetectors. Through in-depth analysis of spectral response data of different types of photodetectors, a machine learning based evaluation model was constructed to achieve accurate prediction and evaluation of the spectral response characteristics of photodetectors.

The research results indicate that machine learning algorithms can effectively identify the response patterns of photodetectors in different wavelength ranges, accurately predict key performance parameters such as spectral responsivity and detection rate of the devices. By comparing traditional laboratory measurement methods, the machine learning based evaluation method proposed in this study has shown significant advantages in both prediction accuracy and efficiency, especially when dealing with complex multivariate spectral response data. The machine learning model can capture potential patterns and correlations that are difficult to discover by traditional analysis methods. The experimental data shows that the established evaluation model achieves a high level of prediction accuracy on the test set, verifying the effectiveness and reliability of the method.

The spectral response function of photodetectors directly affects the accuracy of inversion algorithms and the accuracy of obtaining Earth features. This study not only provides new technical means for the performance evaluation of photodetectors, but also provides important theoretical basis for the optimization design and manufacturing process improvement of optoelectronic devices. Through the analysis of machine learning models, researchers can better understand the influence of different material and structural parameters on the spectral response characteristics of photodetectors, providing guidance for the development of detectors with specific spectral response features.

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Looking ahead to the future, with the continuous development of artificial intelligence technology, the integration and intelligence of optoelectronic detection technology have become the current development trend. This study can be further extended to more types of photodetectors, including emerging two-dimensional material photodetectors, perovskite photodetectors, and so on. Meanwhile, more advanced machine learning methods such as deep learning and reinforcement learning can be introduced into the evaluation of spectral response characteristics to further improve prediction accuracy and model generalization ability.

References

[1] Jiang Yan, Gao Feng, Li Lin. Photodetector with broadband-narrowband dual-function detection mode [J]. Journal of Luminescence, 2024.

[2] Tan Qichuan, Zeng Peng, Yang Zheqi. Design of computationally reconstructed spectral detector based on perovskite filter array [J]. Progress in Laser & Optoelectronics, 2024.

[3] Ge Xinle, Gao Lei, Sun Ling. Preliminary study on spectral response function inversion method based on linear programming [J]. Journal of North China University of Technology, 2024.

[4] Tian Ting, Zhang Qing, Xu Wen. Research progress on the application of spectral technology in crop nutrient monitoring [J]. Jiangsu Agricultural Sciences, 2024.

[5] Liu Sisi, Zhang Bo, Li Xingying, Xin Lei, Ying Guangguo, Chen Chang'er. Research progress on the application of machine learning in environmental analysis and detection [J]. Journal of Analysis and Testing, 2024.

[6] Zhang Haibo, Ji Ting, He Jiayu, Shi Linlin, Li Guohui, Cui Yanxia. Fast-response vertical structure two-dimensional perovskite photodetector [J]. Progress in Laser & Optoelectronics, 2024.

[7] He Yifei, Yang Deren, Pi Xiaodong. Research progress on infrared photodetectors based on silicon two-dimensional layered material heterojunction [J]. Materials Reports, 2024.

[8] Yang Rui, Yang Sishuo, Qian Lingxuan. Study on the influence of oxygen partial pressure on the performance of a-Ga_2O_3-based solar-blind ultraviolet photodetector [J]. Opto-Electronic Engineering, 2024.

[9] Yuan Liu, Zhang Weiqi, Wang Jiaqi, Zhang Hanwen, Wang Yanliang, Jiang Yadong, Tai Huiling. Development of short-wave infrared organic light detection materials [J]. Journal of University of Electronic Science and Technology of China, 2024.

[10] Chen Jianian, Shen Honglie, Li Yufang, Zhang Jingzhe, Li Hechao, Zhang Wenhao. Self-powered Si PEDOT:PSS heterojunction photodetector based on inverted pyramid structure [J]. Journal of Nanjing University of Aeronautics and Astronautics, 2024.

[11] Wang Xiangyong, Wang Qianqian, Dai Lili. Key technologies of LiDAR and their performance requirements in assisted driving [J]. Practical Automotive Technology, 2024.

[12] Wang Tao, Wan Yuemin. Application of stand-alone photoelectric intelligent fire detection technology in ancient buildings in Tibetan areas [J]. Science and Technology Innovation, 2024.