Proceedings of CONF-FMCE 2025 Symposium: Semantic Communication for Media Compression and Transmission
DOI: 10.54254/2755-2721/2025.GL25344

Research on Performance Parameters and Testing Methods of Near-Infrared Photo-Detectors

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Abstract. The study focuses on the performance parameters of near-infrared photo-detectors and their measurement methods to standardize and refine testing technology. It introduces methods for responsivity, detectivity, and response time. Direct measurement methods are highly accurate but complex and harsh, while indirect methods are easy but lack uniform standards in the near-infrared optical band. The detection rate is measured indirectly using noise voltage size and phase-locked amplification technology for improved accuracy. Response time measurement methods include frequency response and impulse response methods, with frequency response having high accuracy but limited applicability and impulse response being intuitive but requiring high bandwidth. Future parameter measurement technology will focus on high precision and fast test development.

Keywords: near-infrared photo-detector, performance parameters, test method, responsivity, detection rate, response time

1. Introduction

Near-infrared (NIR) detectors play a crucial role in the field of optical communication, biomedicine and environmental monitoring. After a long period of in-depth research, NIR detectors have made a series of breakthroughs in terms of material and structure innovation. However, despite significant development over time, the measurement of the performance parameters of NIR photo - detectors still has certain issues. The performance requirements for NIR detectors across various fields, leading to a diverse range of measurement and evaluation metrics. For example, in astronomical observation, parameters such as dark current and signal-to-noise ratio are commonly used to evaluate detector performance [1]. In the field of optical communication, researchers pay more attention to parameters such as response rate and sensitivity [2]. Currently, measuring the performance parameters of photo - detectors also faces numerous challenges. These include noise issues, temperature effects, calibration difficulties, and the problem of how to precisely define their key parameters. This paper focuses on the performance parameters and test methods of NIR detectors, aiming to explore the key performance parameters of NIR detectors and to review, compare and summarize the existing measurement methods. Suggestions are made for how to measure the relevant performance parameters more accurately in the future, and to promote the standardization and precision of the relevant testing techniques.

2. Principle and classification of near infrared detectors

2.1. Operating principle

Near-infrared photo-detectors utilize both external and internal photoelectric effects [3]. The external photoelectric effect detects optical signals by releasing electrons from a photo-cathode's surface. The internal photoelectric effect, on the other hand, involves the photo-conductivity effect and photovoltaic effect [4]. Epiphotoelectric effect detectors, like vacuum photovoltaic devices, improve electron collection efficiency but require a vacuum environment and high-pressure systems. Internal photoelectric effect detectors use semiconductor materials, offering high sensitivity, fast response, simplicity, small size, reliability, and low manufacturing costs [5].

2.2. Common detector types

2.2.1. Semiconductor photo-detector

Semiconductors, including silicon-based and III-V compound materials, graphene, and chalcogenide, are common substrate materials in electronic components [6]. Silicon-based detectors have better electrical performance, carrier mobility, and sensitivity but have a limited wavelength range (1.12EV). Broadening the detectable wavelength range is crucial for combining silicon-based materials with other materials, as they are compatible with CMOS processes [7]. III-V compound semiconductor detectors, made from Group III and Group V elemental materials, have high light absorption coefficients and wide spectral response.

2.2.2. Heat detector

Thermal detectors are commonly used in the near-infrared band due to their thermal effect. They work by converting light energy into thermal energy, which increases the temperature of a photosensitive element. This change in temperature causes changes in the physical parameters of the element, such as resistance and voltage. These changes are then converted into electrical signals, enabling the detection of optical radiation. Common thermal detectors include pyroelectric detectors, thermocouple detectors, and thermistors. Pyroelectric detectors are cost-effective, low-power consumption, and highly sensitive, mainly used for detecting human body radiation. They are commonly used in security monitoring and smart homes [8].

3. The main performance parameters

The performance parameters of NIR photo-detectors are crucial for their applicability and efficiency. The spectral response range refers to the wavelength range within which a photoelectric device can efficiently detect light, varying with wavelength. The response range is influenced by semiconductor material characteristics, device structure, and optical element transmittance. Responsivity: is a physical quantity that measures the efficiency of a photo-detector in converting an input signal (e.g., an optical signal, etc.) into an output signal (e.g., an electrical signal), and the responsivity is defined as the ratio of the photo-current to the incident optical power, which is usually expressed by the formula [9]:

$$R = I_p - I_d / P_{in} \tag{1}$$

Where, R is the responsivity in units of $\mathrm{A/W}$; $\mathrm{I_p}$ is the photo-current, $\mathrm{I_d}$ is the dark current; and $\mathrm{P_{in}}$ is the incident light power.

Specific Detectivity ($\mathrm{D^*}$) is a standardized form of Detectivity (D) and is used to compare the performance of different detectors. It represents the signal-to-noise ratio per unit of radiated power per unit area and per unit bandwidth. Specific Detection Rate ($\mathrm{D^*}$), like Detection Rate (D) is a physical quantity that characterizes the sensitivity of a detector and can be expressed as:

$$\mathrm{D^*} = \mathrm{R}/(2\mathrm{qJ_d})^{1/2} \tag{2}$$

where R denotes responsiveness, denotes unit charge, $\mathrm{J_d}$ denotes dark current density, and $\mathrm{D^*}$ has units of Jones .

Detectivity (D) is an important parameter for measuring detector performance and is defined as the reciprocal of the noise equivalent power (NEP), i.e.

$$\mathrm{D} = \frac{1}{\mathrm{NEP}} \tag{3}$$

The unit is $\mathrm{W^{-1}}$. The higher the detection rate, the better the ability of the detector to detect weak light. Noise equivalent power (NEP) is an important parameter used to describe the detection of weak light by photo-detectors, and is defined as the minimum incident optical power required to produce a signal-to-noise ratio (SNR) of 1 at the output of the detector for a certain modulation frequency, wavelength and effective noise bandwidth. Response time is a crucial parameter in measuring the inertness of a photo-detector [10]. The response time of a device's net photo-current decreases from 10% to 90%, influenced by factors like carrier mobility, channel length, and bias. It's different for photoconductive and photovoltaic devices, and can be influenced by thermal resistance and heat capacity, and material defects [11].

4. Test methods for performance parameters

4.1. Responsiveness test methods

Photodetector responsivity is divided into spectral responsivity and relative spectral responsivity. Spectral responsivity $\mathrm{R}(\lambda)$ is the ratio of the detector output photocurrent $\mathrm{I_p}$ (or voltage $\mathrm{V_p}$) to the incident optical power $\mathrm{P_0}$ at a certain wavelength λ and reverse bias. The relative spectral responsivit $\mathrm{S}(\lambda)$ is the variation of the detector responsivity with wavelength obtained by normalizing the maximum value of the detector spectral response to it [7]. This paper focuses on the measurement of spectral responsivity.

The spectral responsivit $\mathrm{R}(\lambda)$ is usually categorized into voltage spectral responsivity $\mathrm{R_v}(\lambda)$ and current spectral responsivity $\mathrm{R_i}(\lambda)$. The voltage spectral responsivity $\mathrm{R_v}(\lambda)$ and are defined as the signal voltage of the photo-detector output per unit of incident radiant power at a wavelength of λ, and are expressed by the formula:

$$R(\lambda) = \frac{V(\lambda)}{P(\lambda)} \tag{4}$$

And the current spectral responsivity $R_i(\lambda)$ is defined as the photo-current output from the photo-detector per unit of incident radiant power at a wavelength λ.

$$R_i(\lambda) = \frac{I(\lambda)}{P(\lambda)} \tag{5}$$

In both equations, $P(\lambda)$ is the incident optical power at a wavelength of λ, $V(\lambda)$ is the signal voltage output from the photo-detector, and $I(\lambda)$ is the output photo-current in units of A/W or V/W [12].

This paper discusses the limitations of monochromators in measuring spectral responsivity of photo-detectors due to their limited accuracy and wide range of wavelengths. The laser, due to its good monochromaticity, wavelength stability, and simplicity, offers significant advantages in spectral responsivity experiments. The paper compares direct and indirect measurement methods based on amplitude of light accuracy, cost, and environment.

4.1.1. Direct measurement

Direct measurement is a method of measuring incident radiant power per unit of light at a specific wavelength using a cryogenic absolute radiometer (CAR). The direct measurement method usually refers to the method of using a power meter to directly measure the incident radiant power per unit of incident light at a specific wavelength and then calculate the spectral responsivity using the formula. The power meter in the direct measurement method usually uses a cryogenic absolute radiometer (CAR), which adopts the electrical substitution method for the measurement, and determines the incident optical power by accurately measuring the electrical power that produces the same temperature rise [13]. This method is internationally recognized and provides high-precision absolute radiant power measurements. By using low temperature absolute radiometers as reference optical power meters, international comparability and consistency are ensured. However, cryogenic absolute radiometers have drawbacks such as system complexity, high operation and maintenance requirements, and harsh operating conditions. To address these issues, a series of portable standardized transfer detectors based on cryogenic absolute radiometers are being developed to measure spectral responsivity using indirect measurements.

4.1.2. Indirect measurements

With the same wavelength of monochromatic radiation were irradiated with a known responsivity of the standard detector and to be measured detector and their voltage or current, a specific wavelength λ incident light unit of incident radiant power, into the formula to calculate its responsivity, here we take the voltage as an example:

$$R_v(\lambda) = \frac{V_f(\lambda)R_f(\lambda)}{V(\lambda)} \tag{6}$$

$R_v(\lambda)$ refers to the responsivity of the detector to be measured, $V(\lambda)$ refers to the voltage of the detector to be measured, and $R_f(\lambda)$ and $V_f(\lambda)$ denote the responsivity and voltage of the standard detector respectively [14]. The standard transfer detector establishes and delivers infrared spectra response scales with high sensitivity and wide range, ensuring sensitivity and adaptability to elements like light polarization, power, and photosensitive surface position. Reflective trap detectors are ideal in visible wavelengths, but infrared bands have a wide variety due to development challenges and electrical performance limitations [15].

4.2. Detection rate test method

4.2.1. Principle of measuring Noise Equivalent Power (NEP)

Since detectivity (D) and noise equivalent power (NEP) are inversely related, detectivity can be measured indirectly by measuring NEP .

The expression for the noise equivalent power is given below:

$$NEP = \frac{P}{V_s/V_n} \tag{7}$$

Where: P is the radiant optical power incident on the detector, V_s is the rms value of the detector output voltage signal, V_n is the rms value of the detector noise voltage signal [16].

Since the measure of responsiveness is introduced in this paper, $R_v(\lambda)$ is considered as a known quantity in this paper, and combined with Eq. (4) ,Eq. (7) can be expressed as:

$$NEP = \frac{P}{V_s/V_n} = \frac{V_n}{V_s/P} = \frac{V_n}{R_v(\lambda)} \tag{8}$$

Where: V_n is the RMS value of the detector noise voltage signal, R_v is the voltage responsivity [17]. In order to measure the magnitude of NEP it is necessary to measure the RMS value of the noise voltage signal V_n .

4.2.2. Phase-locked amplification technique to measure noise voltage

Noise voltage is a crucial indicator of device performance in photo-detectors. Lower noise voltages perform better and detect weak signals. Phase-locked amplification accurately measures noise voltage by extracting weak signal components with the same frequency as the reference signal. The lock-in amplifier consists of an input module, reference signal module, phase sensitive detection module, and output module shown in Figure1. The phase sensitive detection module multiplies the noise-containing input signal with the reference signal, while the low frequency filter filters out interference and noise.

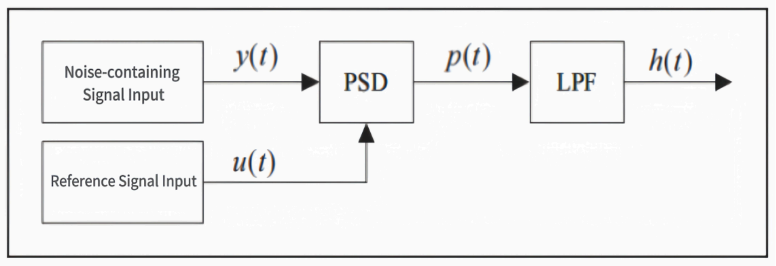

Figure 1. Block diagram of the basic principle of lock-in amplifier

4.3. Response time measurement methods

There are two main methods for measuring response time: the impulse response method and the frequency response method . The next section describes each of these methods.

4.3.1. Frequency response method

The responsivity of a photo-detector varies with the modulation frequency of the incident light, a property known as frequency response. With the help of the time constant, it is possible to derive the relationship between the responsivity of the photo-detector and the incident modulation frequency with the expression [18]:

$$S(f) = \frac{S_0}{\left[1 + (2\pi f\tau)^2\right]^{1/2}} \tag{9}$$

Where $S(f)$ is the responsivity when the frequency is f ; S_0 is the responsivity when the frequency is zero; usually, the response of a photo-detector can be approximated as a first-order RC low-pass filter model with a time constant τ determined by the resistance and capacitance of the detector ($\tau = RC$), a rise time $\tau_T \approx 2.2\tau$, and an upper cutoff frequency for the amplifier.

$$f_r = \frac{1}{2\pi\tau} = \frac{1}{2\pi RC} \tag{10}$$

In the measurement experiment, keep the incident light intensity unchanged, change the incident light frequency, the frequency response curve amplitude-frequency characteristic curve,the horizontal axis is the frequency of f , the vertical axis of Calculation formula is as follows:

$$L_{10} = 20\log_{10}\left(\frac{V}{V_0}\right) \tag{11}$$

Where L_{10} denotes the response bandwidth, V_0 denotes the initial voltage, V denotes the voltage value when changing the frequency of incident light, and V_0 and V can also be replaced by I_0 and I . From the formula(15) can be obtained when the voltage (or current) down to the initial 70.7% of the corresponding decibel number $L_{10} = -3\text{dB}$, then the curve -3dB corresponding to the incident light frequency that is the upper limit of the amplifier's cut-off frequency f_r , by the formula(14) can be obtained from the time constant τ , which leads to τ_r and τ_f .

The frequency response method is based on a circuit's theoretical model; thus, its results exhibit a high degree of accuracy. However, this method assumes that the photo-detector's response can be approximated as a first-order linear RC low-pass filter model. This assumption is not applicable to nonlinear circuits and makes computations extremely difficult in higher-order circuits. Moreover, in actual circuits, there are random factors such as device non - ideality and circuit errors, which may decrease the accuracy of the frequency response method.

4.3.2. Impulse response method

When the photo-detector to an ideal rectangular light pulse irradiation, due to the delay in the response of the detector, its output waveform is no longer an ideal rectangular pulse, but has a certain rising front and falling edge of the waveform, usually defined photo-current from 10% to 90% of the time required to rise or fall is called the response time (rise time and fall time), the use of this feature, when we give the photoelectric Using this property, when we input a pulsed square wave optical signal to the photo-detector, use an oscilloscope to record the waveform of the photo-detector output signal (voltage or current) size over time, and analyze the response period of a single pulse of light according to the definition of the response time can be obtained. This method is simple and intuitive, but requires a laser with a bandwidth at least 3 to 5 times the bandwidth of the device under test, which results in the measurement of larger bandwidth photo-detectors, it is usually not possible to find a laser with the appropriate bandwidth size, limiting its application in the measurement of high-speed photo-detectors [10].

5. Trends in testing technology

High-precision test technology is being developed using advanced optical and electronic technologies to improve precision. Low-noise amplifiers are being used to reduce signal amplification noise and improve the signal-to-noise ratio, enabling accurate measurement of photo-detectors' responsiveness and noise equivalent power. Li Weiye's high-precision low-noise operational amplifiers have excellent low-noise characteristics. High-precision spectrometers are being used for accurate wavelength selection and optical power measurement, and spectral responsivity measurement. Rapid testing technology, including parallel testing and real-time monitoring, is being developed to meet the needs of large-scale production and rapid research and development. These technologies allow for real-time data analysis, problem identification, and correction, promoting rapid research and quality control in production. This allows for monitoring performance parameters, adjusting test conditions, and production processes to ensure product quality.

6. Conclusion

In this paper, the main performance parameters of near-infrared photo-detectors and their testing methods are studied in depth. The performance parameters include spectral response range, responsivity, detectivity, noise-equivalent power (NEP) and response time, which are affected by various factors such as material properties, device structure and working environment. There are still some problems and deficiencies in the current research. For example, some test methods have limitations. The direct measurement method has high accuracy but requires demanding equipment, while the indirect measurement method is convenient yet has not formed a unified standard in the near-infrared band. In addition, the performance parameters of new detector materials (e.g., two-dimensional materials, chalcogenides, etc.) have not been studied deeply enough, and there is a lack of targeted test methods and evaluation standards. The phase-locked amplification technique can effectively improve the accuracy of the detection rate test; the frequency response method is suitable for detectors with a first-order linear model, and the impulse response method is more intuitive but requires a high bandwidth for the equipment. Future research should optimize existing test methods, develop new techniques for new detector materials, strengthen standardization and normalization, promote data comparability, and promote near-absolute detection rate tests. This will help reduce equipment and environment requirements, enhance the overall development and application of NIR photo-detector technology.

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