Current Natural Sciences

ELECTRONIC ENGINEERING

Yihua HU

Theoretical Framework and Techniques for Laser Detection Utilizing Coherence

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This book introduces the theories and methods of laser coherent detection in the field of high-performance target detection. It includes five chapters, including the theoretical foundation of laser coherent detection, laser coherent detection of atmospheric disturbances, the chirped amplitude-modulated (AM) laser coherent detection of range and velocity, laser coherent detection based on the micro-Doppler effect, and laser coherent detection of synthetic aperture lidars (SALs).

The book offers an invaluable resource for researchers, especially those who are engaged in fields including laser imaging, photoelectric information acquisition, target detection and recognition, and laser technology. Additionally, it can be used as a reference book for professional teachers, advanced undergraduates, and postgraduates of relevant majors.

Professor **Yihua Hu** is Professor and the Director of the State Key Laboratory of Pulsed Power Laser Technology, National University of Defense Technology. **Hu** is a Fellow of Chinese Optical Society, the Chinese Institute of Electronics and Vice-Chairman of Anhui Association for Science and Technology. **Hu** is a leading authority in the fields of laser detection with renowned expertise in 3-D laser detection theory and its application, including characterization and modeling of modulated laser echoes, 3-D structure detection, recessive characteristics detection, and precise imaging. His research has been applied in Chang 'e exploration project. He has won multiple prizes such as the National Technological Invention Award, Anhui Major Achievement Award for Scientific and Technological, and eight first prizes at the provincial and ministerial levels. **Hu** is the author of four academic books on laser detection and has published more than 100 articles in peer-reviewed journals, such as Science China Materials, Optics Express, and IEEE Transactions on Geoscience and Remote Sensing.

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Preface

In the information and intelligent age, people need to perceive the world around them all the time, and the more accurate, more reliable and faster, the perception is the better. Laser detection, as an active non-contact detection method, can quickly acquire more target information at long distances. Characterized by the short wavelength and narrow beam, laser detection can achieve high measurement accuracy and has good anti-jamming capability to make information perception more reliable. At present, laser detection has become a highly regarded means of information acquisition and has received attention from researchers in fields such as the military, remote sensing, and aerospace. Technology has developed rapidly and has found many applications.

Laser coherent detection, as a frontier researching direction of laser detection, has many advantages because it detects the information of optical carriers modulated by targets, rather than light intensity alone. These advantages include high conversion gain, excellent filter performance, abundant detectable information characteristics, and high sensitivity. Compared with direct detection, it is of great value in the application of high-precision target detection. Laser coherent detection can obtain the range, motion velocity, and micro-motion of hard and soft targets by detecting changes in the optical frequency and phase of laser echoes. Setting the sights on light intensity detection of laser echoes at the absorption wavelength, the components of gaseous and particulate targets can be determined by measuring their absorption parameters. Synthetic aperture imaging of targets can be realized by fusion processing coherent echoes of multi-beam. According to the operating principle, laser coherent detection sets high requirements for the coherence of laser sources. Whereas, the coherence of target echoes is affected by lots of factors, which renders it difficult to detect and process signals and implement the technology. Given this, numerous scholars at home and abroad have studied theoretical and technical issues related to the practical application of laser coherent detection.

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Laser coherent detection is bound to have good development opportunities and broader application prospects in the future.

As time flies, it has been nearly 30 years since Professor Yihua Hu joined our team to develop research on laser detection technology. In the early 1990s, I had the honor to invite Professor Hu to take part in the project "airborne three-dimensional (3D) imager" (topic 308 in National High Technology Research and Development Program of China (863 Program)) that I organized. The project made breakthroughs in the ground scanning ranging based on laser direct detection and took the lead way in developing an airborne laser-infrared remote-sensing imaging system. On this basis, Professor Hu participated in the lunar exploration project of China, in which the core load, the laser altimeter, on the lunar probe satellite Chang 'e-1 was developed, which is the first remote-sensing laser system for space usage in China. Additionally, the digital elevation model of the complete lunar surface best in the world then was established. Afterwards, Professor Hu applied laser detection to moving target detection combining his tasks in the new position. Apart from further carrying out in-depth laser direct detection and developing 3D imaging of aerial targets, Professor Hu also leads a team to study and apply laser coherent detection to moving target measurements of higher accuracy. After more than 20 years of hard work, his team has achieved pioneering research results at home and abroad in target detection, accurate target ranging and velocity measurement, detection of target micro-motion characteristics, and high-resolution synthetic aperture imaging and detection of targets. The team has gradually developed new target detection methods.

This monograph "*Theoretical Framework and Techniques for Laser Detection Utilizing Coherence*" summarizes the research findings of Hu's team in the theory and application of laser coherent detection. It emphasizes four key technologies in laser coherent detection, namely, detection of atmospheric disturbances induced by moving targets, ranging and velocity measurement of high-speed moving targets, micro-Doppler-based detection, and synthetic aperture imaging. In addition, the monograph also introduces a series of laboratory experiments, field verification experiments, and some applications. Most of the cases are from first-hand research conducted by the author's team and they are useful to researchers, teachers, students, and engineers in related fields.

There is still a long way to go for the application of laser coherent detection. Systematic theory and technical monographs in this field are still scarce at home and abroad. I believe that the publication of this monograph will enrich the theory of laser coherent detection, which is a valuable effort and provides an important reference for the applied research of laser coherent detection. It is also hoped that the author's team can continue to study intensively in this direction and achieve better research results.

Yongqi Xue
Academician of Chinese Academy of Sciences
Researcher of Shanghai Institute of Technical Physics, CSA
May, 2022

Foreword

Laser is another discovery of great significance by humans after semiconductor and nuclear energy. By using the excellent properties of laser, including high coherence and narrow beam, people have applied the laser to active acquisition of target information, thus developing the laser detection technology, which has been widely applied to many fields. These include science research, deep space exploration, environmental monitoring, ocean exploration, forest survey, topographic mapping, and military domain. For example, it has been applied to the atmosphere, land, and ocean exploration in the geoscience field; to satellite-earth remote sensing, inter-satellite ranging, fragment detection, and space rendezvous and docking in the aerospace field; to detection of particulate matter, polluting components, visibility, and quietness in the environment and meteorology field; to the establishment of digital elevation models, topographic mapping, and forest stock investigation in the mapping and resource field; and reconnaissance and imaging, space surveillance, target measurement, obstacle avoidance, underwater target detection, and chemical/biological warfare agent detection in the military application domain.

According to the detection style, laser detection can be divided into direct detection and coherent detection. Direct detection directly transforms laser signal intensity into electrical signals, where the amplitude of the output from photoelectric detectors is directly proportional to the received optical power. Target information is contained in the signal amplitude and travel time. Coherent detection coherently mixes laser echo and local-oscillator (LO) signals on the detector and outputs intermediate frequency (IF) signals, in which target information is modulated. Relevant information on targets can be obtained by processing IF signals. Due to the introduction of LO signals, coherent detection improves the detection sensitivity and reduces the minimum detectable power. It can also acquire the phase and frequency variation of laser echoes, so laser coherent detection outperforms direct detection in terms of measurement accuracy. With advantages including high sensitivity, abundant detectable information characteristics, and high conversion gain,

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it can achieve high-accuracy target detection and recognition. Given this, laser coherent detection has gotten more and more attention and become one of the research focuses all over the world. However, laser coherent detection systems feature complex structures and set a high requirement for the coherence of light sources. Additionally, the detection platform, the atmosphere in the transmission channel, and the target itself heavily affect the coherence of laser echoes and it is also difficult to extract target-modulated optical frequencies from weak signals. As a result, coherent detection has not been widely applied.

The author has been engaged in the research of target laser detection for a long time and has conducted a number of national and military research projects. Starting with airborne laser ranging, the author has studied laser direct detection, developed the first remote-sensing laser system for space use, that is, the laser altimeter on the lunar probe satellite Chang 'e-1, and then developed a 3D target laser imaging system. Meanwhile, the author leads a team to carry out in-depth research on laser coherent detection, accumulate abundant first-hand data, publish a series of papers, apply for a batch of patents, and develop experimental or application systems. This monograph was written by summarizing years of research achievements of the team in laser coherent detection, aiming to systematically expound theoretical methods of laser coherent detection oriented to target detection.

The monograph includes five chapters, laying emphases on discussing the theoretical methods and research achievements of laser coherent detection in atmospheric disturbance detection, ranging and velocity measurement, micro-Doppler-based detection, and synthetic aperture detection. Chapter 1 provides the theoretical foundation of laser coherent detection and mainly introduces the fundamentals, principles, main technology indexes and their characteristics, application situation, and typical systems of laser coherent detection. Chapter 2 introduces laser coherent detection of atmospheric disturbances and describes two aspects (atmospheric CO_2 and wind-field disturbances induced by moving targets) following the idea of detection principle, detection system, and experimental verification. Chapter 3 describes the chirped amplitude-modulated (AM) laser coherent detection of range and velocity and mainly introduces the principles, methods, and systems for ranging and velocity measurement of chirped AM lidars. Chapter 4 introduces laser coherent detection based on the micro-Doppler effect, and expounds its modeling as well as rapid extraction of micro-motion characteristics based on time–frequency analysis (TFA) and micro-motion parameter estimation based on the signal model. Focusing on synthetic-aperture laser coherent detection, chapter 5 describes laser coherent detection of synthetic aperture lidars (SALs) and introduces the detection principle, imaging algorithm, phase compensation algorithm, and experimental systems, and verification of SALs.

Research in the monograph was conducted by the author's team in the College of Electronic Countermeasures, National University of Defense Technology (former Electronic Engineering Institute of PLA) and Shanghai Institute of Technical Physics, Chinese Academy of Sciences (CSA). In the process, the research team was carefully guided and vigorously supported by experts including academicians Yongqi Xue, Guangcan Guo, Wei Huang, Lijun Wang, Wei Wang, Wenqing Liu,

Bangkui Fan, and Jianyu Wang, who also provided valuable comments and suggestions for the draft. The research has always been supported and assisted by leaders of the College of Electronic Countermeasures, institutions, and team members. Professor Wuhu Lei, Professor Shiqi Hao, associate Professor Nanxiang Zhao, and researcher Xing Yang in the College of Electronic Countermeasures, as well as researchers Rong Shu, Genghua Huang, and Guanglie Hong in Shanghai Institute of Technical Physics, have made great contributions and provided strong support for the research. Members of the research team and tens of master's degree candidates supervised by the author have taken part in part of the research. In the drafting process, associate Professor Wen Lu, doctors Liang Shi, Xinyuan Zhang, and Xiao Dong took part in data collection and text arrangement. I would like to express my heartfelt thanks to all the people who provided support and assistance with the monograph. I would like to express my sincere thanks to the authors of many valuable Chinese and foreign literature referred to and to the Science Press for their enthusiastic support in the preparation and publication of this monograph.

The monograph only represents the tip of a giant iceberg in the research of laser coherent detection and some problems remain to be further deeply studied. Due to the limited knowledge of the author, there might be inevitably some mistakes and flaws in the monograph. Comments from experts and readers are welcomed.

Yihua Hu
Hefei, May 2024

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Chapter 1

Theoretical Basis of Laser Coherent Detection

Laser is honored as the magic light. It has been more than one century since 1916 when Albert Einstein proposed the theory of stimulated emission of radiation, followed by the invention of the first laser beam in 1960. Laser has obvious advantages, including good directivity, small angle of divergence, extreme brightness, large energy density, pure color, good monochromaticity, and high coherence. Laser coherent detection is one of the main ways of laser detection. Compared with direct detection, laser coherent detection has advantages including high conversion gain, favorable filter performance, abundant detectable information characteristics, and high sensitivity. Therefore, it has been widely applied to the high-accuracy detection of targets. Starting with the basic concept of laser detection, the chapter introduces the fundamental principles, main technology indexes, characteristics, and typical applications of laser coherent detection.

1.1 Overview of Laser Detection

Like nuclear energy and semiconductors, the laser is another major discovery of humans. Laser is the acronym for "light amplification by stimulated emission of radiation", which has fully expressed the main generation process of laser: light radiated by stimulated atoms.

A radar that uses a laser as the source of radiation for target detection is called a lidar, which is the typical laser detection system. Taking laser as the carrier, lidars carry information using the amplitude, wavelength, phase, or polarization and finally achieve the target detection function by combining with different transceiver systems[1].

The light and microwave both belong to electromagnetic waves, so lidars and microwave radars do not have essential differences in terms of the detection principle. The difference not only lies in that the laser wavelength is far shorter than microwave wavelength, but also in the generation, emission, modulation, and receiving modes. Compared with microwave radar detection, lidar detection mainly has the following advantages[2]:

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(1) Extremely high angular resolution. According to the Rayleigh criterion, the resolution is in direct proportion to the wavelength while in negative proportion to the receiving aperture. The wavelength of lidars is mainly in the near-infrared, visible, and ultraviolet bands, which are far smaller than microwaves, so an extremely high resolution can be obtained even if a small receiving aperture is used.
(2) Extremely high range resolution. Similar to pulse ranging, the laser pulse width can be as narrow as picoseconds, which corresponds to a range resolution at the millimeter level. In addition, laser beams are narrow and have a small footprint, which also helps to improve the range resolution.
(3) High Doppler velocity resolution. During the relative motion of a target in the line-of-sight of a radar, the magnitude of the Doppler shift generated by received echoes is negatively proportional to the wavelength. Because lidars have a wavelength far shorter than microwaves, their Doppler shift is in a larger range, which is conducive to realizing extremely high-velocity resolution.

According to the difference in detection targets, laser detection can be divided into two types. One is "soft" target detection, which detects the properties of atmospheric substances in the laser transmission path, such as atmospheric component, wind field, and turbulence measurement, based on atmospheric backscattering; the other is "hard" target detection, which detects ontological attributes of targets, such as moving target reconnaissance, based on laser reflection by target surfaces.

According to the difference in detection modes, laser detection can also be divided into two types: direct detection and coherent detection. Direct detection directly converts laser signals into electrical signals. The amplitude of electrical signals output by photoelectric detectors is directly proportional to the received optical power. Direct detection does not require coherence of signals, so it is also called non-coherent detection. Coherent detection outputs intermediate-frequency (IF) heterodyne signals by mixing two laser signals, namely, echo and local-oscillator (LO) signals at the optical frequency. Compared with direct detection, coherent detection can not only obtain the intensity of optical signals but also acquire information including the frequency and phase.

At present, laser detection has become an important active target remote-sensing and detection method attributed to its high measurement accuracy, fine temporal and spatial resolutions, and longer detection range. It has a wide application prospect in civil and military fields. In the civil field, laser detection is mainly used for meteorology, ocean, environment, surveying and mapping, and deep space exploration[3]. As for military use, laser detection is mainly applied to laser reconnaissance, target ranging, velocity measurement, imaging and recognition, tracking and pointing, precision guidance, etc[4]. Laser coherent detection, as an important development direction of laser detection technology, has played an increasingly important part in various target detection fields.

1.2 Principles of Laser Coherent Detection

Compared with direct detection, laser coherent detection can acquire not only the echo intensity of objects but also the phase and frequency of light echoes. This section mainly introduces the principles of laser coherent detection from two aspects:

the square-law characteristic of photoelectric detectors and the characterization of detected signals.

1.2.1 Square-Law Characteristic of Photoelectric Detectors

Laser coherent detection is to realize the coherence and mixing of optical signals based on the square-law characteristic of photoelectric detectors. Photoelectric detectors transform the received echo signals into electrical signals, and the output photocurrent $i_{\mathrm{D}}(t)$ is in direct proportion to the echo power $P(t)$, that is, $i_{\mathrm{D}}(t) = \alpha P(t)$. Therein, t is time and α is the conversion coefficient (responsivity) of photoelectric detectors.

Assuming that the electric field of a linearly polarized optical wave is $e(t) = E\cos(2\pi ft + \varphi)$, in which E is the optical field amplitude of the signal, f is signal optical frequency, and φ is the initial phase. Because the period of vibration of light is far shorter than the response time of detectors, detectors cannot respond to optical-frequency components and can only respond to the average energy or power of optical signals. The average optical power P is expressed as follows:

$$P = \overline{e^2(t)} = E^2\overline{\cos^2(2\pi ft + \varphi)} = \frac{E^2}{2}\overline{[1 + \cos(4\pi ft)]} = \frac{E^2}{2} \tag{1.1}$$

where $\overline{e^2(t)}$ is the average value of $e^2(t)$. Then, the output photocurrent I of photoelectric detectors is

$$I = \alpha P = \frac{\alpha E^2}{2} \tag{1.2}$$

If the load resistance of detectors is R_{L}, then the electric power output by photoelectric detectors is

$$P_{\mathrm{e}} = I^2 R_{\mathrm{L}} = \alpha^2 R_{\mathrm{L}} P^2 \tag{1.3}$$

It can be seen from equation (1.2) that the photocurrent output by photoelectric detectors is in direct proportion to the square of optical field amplitude; equation (1.3) shows that the electric power output by photoelectric detectors is directly proportional to the square of incident optical power. This is the square-law characteristic of photoelectric detectors.

1.2.2 Characterization of Laser Coherent Detection Signals

In laser coherent detection, the signal light to be detected and LO light are incident onto the photosensitive surface of photoelectric detectors at the same time, forming the interference patterns of light. Photoelectric detectors respond to the interference optical fields of the two beams, thus outputting photocurrent converted by mixing.

The photocurrent signal is not only related to the incident light intensity but also to the frequency and phase. Figure 1.1 shows the schematic diagram for the principles of laser coherent detection.

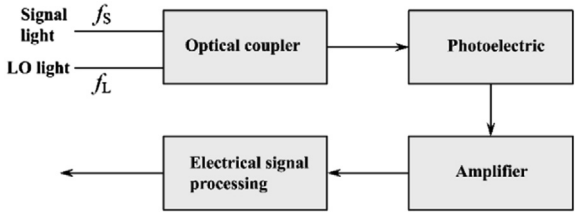


FIG. 1.1 – Schematic diagram for the principles of laser coherent detection.

Assuming that the electric fields of signal light and LO light are $e_S(t)$ and $e_L(t)$, which are both linearly polarized light and have the same polarization direction, as shown below:

$$e_S(t) = E_S \cos(2\pi f_S t + \varphi_S) \tag{1.4}$$

$$e_L(t) = E_L \cos(2\pi f_L t + \varphi_L) \tag{1.5}$$

where E_S and E_L are the amplitudes of signal light and LO light; f_S and f_L are frequencies of signal light and LO light; φ_S and φ_L are initial phases of signal light and LO light, respectively. When the coherence conditions are met, the two light beams are incident onto the photoelectric detector along the same direction and completely matched. The electric field $e_D(t)$ on the photosensitive surface of the photoelectric detector is the superposition of signal light and LO light, that is,

$$e_D(t) = E_S \cos(2\pi f_S t + \varphi_S) + E_L \cos(2\pi f_L t + \varphi_L) \tag{1.6}$$

The following photocurrent $i_D(t)$ induced by the photoelectric detector is obtained by using equations (1.2) and (1.6):

$$\begin{aligned} i_D(t) &= \alpha \overline{e_D^2(t)} = \alpha \overline{[e_S(t) + e_L(t)]^2} \\ &= \alpha \overline{[E_S \cos(2\pi f_S t + \varphi_S) + E_L \cos(2\pi f_L t + \varphi_L)]^2} \\ &= \alpha \overline{E_S^2 \cos^2(2\pi f_S t + \varphi_S) + E_L^2 \cos^2(2\pi f_L t + \varphi_L) + 2E_S E_L \cos(2\pi f_S t + \varphi_S)\cos(2\pi f_L t + \varphi_L)} \end{aligned} \tag{1.7}$$

Due to the bandwidth limitation of the photoelectric detector, the above formula is simplified as

$$\begin{aligned} i_D(t) &= \frac{1}{2}\alpha E_S^2 + \frac{1}{2}\alpha E_L^2 + \alpha E_S E_L \cos[2\pi(f_S - f_L)t + (\varphi_S - \varphi_L)] \\ &= \alpha(P_S + P_L) + 2\alpha\sqrt{P_S P_L}\cos[2\pi(f_S - f_L)t + (\varphi_S - \varphi_L)] \end{aligned} \tag{1.8}$$

where P_S and P_L are powers of signal light and LO light obtained using equation (1.1), that is, $P_S = E_S^2/2$ and $P_L = E_L^2/2$. It can be obtained using equation (1.8) that the photocurrent of photoelectric detectors is composed of two parts: one is the DC power term and the other is the difference frequency term.

The frequency difference between the signal light and LO light is called IF f_{IF}, that is, $f_{\mathrm{IF}} = f_{\mathrm{S}} - f_{\mathrm{L}}$. If $f_{\mathrm{S}} \neq f_{\mathrm{L}}$, it means heterodyne detection; if $f_{\mathrm{S}} = f_{\mathrm{L}}$, it means homodyne detection. Under the condition of $f_{\mathrm{S}} \neq f_{\mathrm{L}}$, the IF current output by the detector is

$$i_{\mathrm{IF}}(t) = 2\alpha\sqrt{P_{\mathrm{S}}P_{\mathrm{L}}}\cos[2\pi(f_{\mathrm{S}} - f_{\mathrm{L}})t + (\varphi_{\mathrm{S}} - \varphi_{\mathrm{L}})] \tag{1.9}$$

The above expression of the IF current is the result under the ideal condition, which is established when the optical fields of LO and echo signals are completely matched. This requires overlapped light spots with the same size, matched beam wavefronts, the same incident angles when radiated on the detector, and the same polarization state of light beams. However, in fact, it is impossible to achieve complete spatial phase matching, so the actual IF current can be expressed as follows:

$$i_{\mathrm{IF}}(t) = 2\alpha\eta_{\mathrm{h}}\sqrt{P_{\mathrm{S}}P_{\mathrm{L}}}\cos[2\pi(f_{\mathrm{S}} - f_{\mathrm{L}})t + (\varphi_{\mathrm{S}} - \varphi_{\mathrm{L}})] \tag{1.10}$$

where η_{h} is the coherent detection efficiency, $\eta_{\mathrm{h}} = \eta_{\mathrm{C}}\cos\gamma$. Therein, η_{C} is the reduction of coherence efficiency due to unmatched light beams (except for polarization matching), $\cos\gamma$ is the reduction of coherence efficiency due to unparallel polarization directions, and γ is the angle between polarization directions of LO and echo signals.

It can be seen from equation (1.10) that frequency $f_{\mathrm{S}} - f_{\mathrm{L}}$ and phase $\varphi_{\mathrm{S}} - \varphi_{\mathrm{L}}$ both change in proportion to the frequency and phase of signal light. The voltage $v_{\mathrm{IF}}(t)$ of IF signals output by the detector is

$$v_{\mathrm{IF}}(t) = 2\alpha\eta_{\mathrm{h}}R_{\mathrm{L}}\sqrt{P_{\mathrm{S}}P_{\mathrm{L}}}\cos[2\pi(f_{\mathrm{S}} - f_{\mathrm{L}})t + (\varphi_{\mathrm{S}} - \varphi_{\mathrm{L}})] \tag{1.11}$$

where R_{L} is load resistance. The effective power of output IF signals P_{IF} is the average value of instantaneous IF power in the IF period, as expressed below:

$$P_{\mathrm{IF}} = \frac{\overline{v_{\mathrm{IF}}^2(t)}}{R_{\mathrm{L}}} = 2\alpha^2\eta_{\mathrm{h}}^2 P_{\mathrm{S}}P_{\mathrm{L}}R_{\mathrm{L}} \tag{1.12}$$

1.3 Signal-to-Noise Ratio of Laser Coherent Detection

1.3.1 Noise of Photoelectric Detectors

Due to a random fluctuation of optical signals incident on photoelectric detectors and statistical characteristics of the generation and collection process of photoelectrons, the photocurrent contains not only signal but also noise. The noise mainly includes shot noise, thermal noise, and $1/f$ noise, along with dark current noise, background noise, and multiplication noise[5]. The sources of noise in photoelectric systems are displayed in figure 1.2.

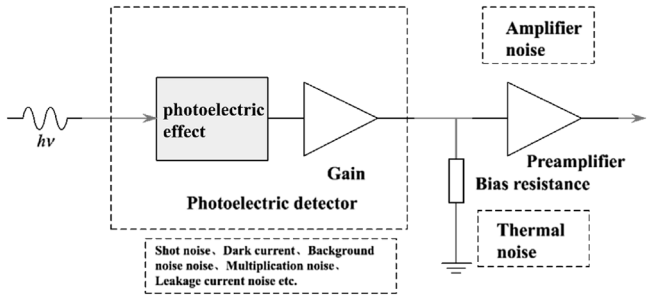


FIG. 1.2 – Sources of noise in photoelectric systems.

(1) Shot noise. The photoelectric conversion process of photoelectric detectors is a random process of photoelectron counting. The photocurrent is the statistical result of the process, which randomly fluctuates in the unit of electron charges. As the result of such random fluctuation, shot noise has a power spectrum of $g(f) = eIM^2$, in which I is the average current of detectors, M is the gain of detectors, and e is the electron charge. The power spectrum of shot noise does not vary with the frequency, so it belongs to white noise. For a photoelectric detector with the bandwidth of B and bias resistance of R_{L}, the shot-noise current i_{N} and voltage v_{N} are expressed as

$$i_{\mathrm{N}} = \sqrt{eIBM^2}, \quad v_{\mathrm{N}} = \sqrt{2eIBR_{\mathrm{L}}^2M^2} \tag{1.13}$$

(2) Thermal noise. Random thermal collision of free electrons in the equivalent resistor R in detectors generates randomly fluctuating voltage on both sides of the resistor, that is, thermal noise of the resistor, of which the power spectrum is $g(f) = 2kT/R$. The thermal noise is also white noise. Therein, k is the Boltzmann constant ($k = 1.380649 \times 10^{-23}$ J/K) and T is the detector temperature. The thermal-noise current i_{N} and voltage v_{N} are expressed as

$$i_{\mathrm{N}} = \sqrt{4kTB/R}, \quad v_{\mathrm{N}} = \sqrt{4kTRB} \tag{1.14}$$

(3) $1/f$ noise. $1/f$ noise mainly occurs at a low frequency below 1 kHz, of which the power spectrum is negatively proportional to the power. Such noise is derived from manufacturing defects of detector surfaces, and it is the dominant noise at low frequencies.

(4) Dark current noise. Dark current noise is the shot noise induced by hole-electron pairs formed randomly by the internal thermal effect of detectors without light incidence. Factors influencing the magnitude of dark current noise include materials of devices, bias voltage, and operating temperature.

(5) Multiplication noise. Multiplication noise is additional noise generated randomly in the multiplication process of avalanche photodiodes and it increases with growing multiplication gain. The dark current is multiplied in the avalanche photodiode and exerts more great influences.