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Development of a high-speed optical system for lightning flash observation

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ABSTRACT

To study the lightning attachment process of cloud-to-ground lightning flash, we develop a high-speed optical system of photodiodes array named Lightning Leader Progression Feature Photic Observation System (LiPOS) for lightning flash observation. It consists of power supply, signal capture, noise suppression, signal conditioning and collection, and electromagnetic shielding modules. The designed observation circuit mounted at the camera's film plane of a 50 mm lens contains eight light receiving channels of photodiodes which are arranged in a vertical array. The system can use time difference of arrival of light signals in different receiving channels to determine the velocity. Besides, the specially designed T-type feedback network of the conditioning module can improve the stability of the amplifying circuit, while the noise suppression and electromagnetic shielding modules can provide the anti-interference ability for the LiPOS. In particular, we design and make a laser source with fast rise time to test the temporal resolution. It shows that the waveforms with rise time over 39.6 ns can be measured by the designed LiPOS. Moreover, the observation of the spark gap experiment is carried out to validate the LiPOS. The experimental results show that the observed 1-D velocities are 1.53×10^7 and 4.32×10^6 m/s, respectively.

1. Introduction

The understanding of the attachment process of cloud-to-ground (CG) lightning flash, which starts with the leader development and ends with the return-stroke stage [1], is an important aspect for lightning protection design as it can determine the striking point of grounded objects. Nevertheless, since the stochastic characteristics of lightning flash lead to a complicated and variable propagation process, the detailed physics of the attachment process is still not sufficiently resolved [2]. Compared with the measurement from the lightning electromagnetic field [3,4], the optical observation can directly obtain the velocity and luminosity of the leader channel. However, as the initiation process of the lightning usually occurs on a time scale of less than 1 μs and on a spatial scale of some meters to tens of meters [5], it is challenging for the high spatial and temporal resolution observation of upward- connecting leader due to such short duration time and small scale.

The most effective tool for the observation of lighting attachment process is the high spatial and temporal photography. Schonland et al. [6] firstly carried out the observation of lightning flash with highly time-resolved streak photography. These photographs were captured by a Boy camera equipped with a moving lens and the effective time resolution is about 5 μs. Berger et al. [7] recorded the evidence of corona discharge at the tip of an upward negative leader channel by using streak photography with moving film tape. Idone et al. [8] used streak photography to observe the triggered lightning at ultraviolet wavelengths and found the dart leader shown a stepwise propagation characteristic. Many researchers used the streak camera for lightning observations, which has made a significant contribution to the basic understanding of the lightning flash. However, the drawbacks of the streak photography include the limited temporal and spatial resolutions and the non-linear response to the light intensity [9].

Since the high-speed video camera can directly obtain the development process and luminosity of lightning flash, it has replaced the streak photography. The high-speed video camera is available for its short exposure time and high frames rates, allowing the possibility of capturing the spatial and temporal resolved sequential images of lightning attachment process. Hill *et al.* [10] presented the high-speed video images of the lightning stepped leader at a frame rate of 300,000 frames per second with 3.33 μs exposure time. Petersen et al. [11] used a high-speed video camera operated at 10,000 frames per second to image a natural negative

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stepped leader and subsequent dart-stepped leader process. Biagi et al. [12,13] carried out extensive observations of triggered lightning with the high-speed video at frames rates of 50,000 and 240,000 frames per second, respectively. Nevertheless, to achieve high frames rates, it will lead to the reduction of the camera's view for the high-speed video camera, resulting in the incomplete recording of lightning flash.

According to the observations in the laboratory-generated long sparks and triggered lightning experiments, the temporal resolution of the camera should be less than 3.33 μs to clearly capture the initiation process of leader [14]. However, to obtain large view and high spatial resolution, the video camera is not always operated at very high frames rates in the practical application. Hence, the high speed optical system with temporal resolution of sub-microsecond is necessary for lightning flash observation. With the development of video camera technique along with the digital sampling and recording methods, the researchers can realize finer resolution and increase linearity of data acquisition. Mach et al. [15] developed a photoelectric technique for measuring the lightning return-stroke velocity with a 10%- 90% rise time of 0.6 μs for the amplifying circuit. Wang et al. [16,17] used the Automatic Lightning Progressing Feature Observation System (ALPS) to reveal the upward-connecting leader and corresponding bidirectional propagation feature of return stroke both in triggered and natural lightning flashes. Due to the narrow dynamic range, short recording time and small view angle, Wang et al. [18] designed the Lightning Attachment Process Observation System (LAPOS) for lightning observation. While the above mentioned literatures have contributed to the study of the high speed observation systems, it still needs to do extensive work on the development of the observation systems with higher temporal and spatial resolutions.

The high sensitive photodiode array has a higher temporal resolution compared with the high-speed video camera. It can provide a deep analysis inside the lightning attachment process and has a low cost. To study the lightning attachment process of the cloud-to-ground lightning flash, we developed a high speed observation system named Lightning Leader Progression Feature Photic Observation System (LiPOS) which can measure the waveforms with rise time over 39.6 ns. The LiPOS consists of power supply, signal capture, noise suppression, signal conditioning and collection, and electromagnetic shielding modules. The tests have shown that the designed LiPOS can meet the requirements in the observation of lightning flash.

2. Design principles of the LiPOS

2.1. System overview

The designed LiPOS can capture the optical signals when the lightning flash enters the view of the camera. The photodiodes are arranged in a vertical array. All diodes are silicon S2551 with an effective active area of 1.2 × 29.1 mm^2. When the temperature is typical value of 25 °C, the spectral responses of S2551 is shown in Fig. 1. The observation circuit is mounted at the camera's film plane of a 50 mm lens. When the light enters the view of the camera, it will be converted to electrical signals by the photodiodes. After the signal conditioning and noise suppression, the electrical signals will be recorded by the acquisition card. Fig. 2 shows the divisions of the camera's view. The photodiodes arrays are configured to form 8 horizontal lines.

The system schematic diagram is shown in Fig. 3. The designed LiPOS consists of the power supply, signal capture, noise suppression, signal conditioning and collection, and electromagnetic shielding modules.

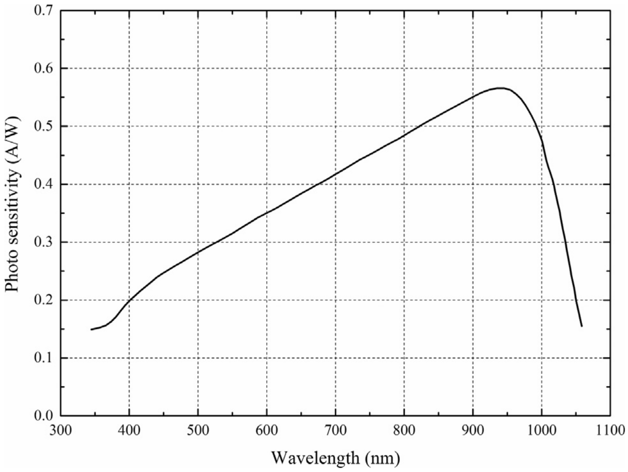

Fig. 1. Spectral responses when the temperature is typical value of 25 °C.

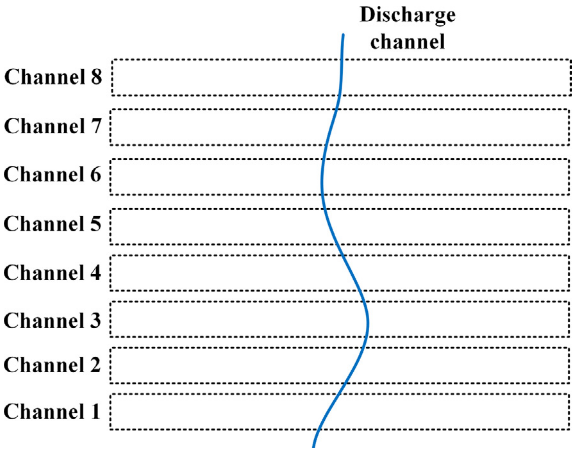

Fig. 2. The divisions of the camera's view.

The signal capture module contains the camera lens and photodiodes array. First, the light signals pass through the camera lens. The photodiodes array will receive the light signals and converts them into electric signals. Then, the noise suppression module denoises the background noise of the electric signals. The signal conditioning module composed of T-type mutual impedance amplification circuit amplifies the signals and converts them into voltage signals which are proportional to the received light intensity. The voltage signals are then fed into data collection module to accomplish data acquisition. The 220 V AC is rectified and regulated into 6 V DC to provide a stable power supply for the signal capture and conditioning modules during the observation. To avoid the lightning electromagnetic interference, the power supply, signal capture, noise suppression and signal conditioning modules are shielded.

2.2. Method to determine the initiation point

To accurately measure the leader speed, it is necessary to find the initiation points of different channels. The slope-intercept method is adopted in this paper to search the initiation points of the measured waveforms [9]. Fig. 4 shows the so-called slope-intercept method to determine the initiation point.

As shown in Fig. 4, two dashed lines are drawn, one along the average noise level prior to the rising edge and the other one along the average slope of the measured waveform. The intersection