Rotation Angle Measurement of Propagating Beam Polarization under High-Voltage Discharge

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Abstract

When lightning discharges occur in the atmosphere, the polarization plane of a propagating beam undergoes rotation due to the magneto-optical effect (Faraday effect). In this study, the application of lidar to measurement of lightning strokes is considered. The rotation angle of the beam polarization plane under the experimental model of a high-voltage discharge was estimated. A laboratory experimental apparatus for measuring the rotation angle using repeating mirror optics was constructed for preliminary experiments.

1.Introduction

Damage due to lightning strokes could be avoided if the electromagnetic field in the atmosphere and air ionization process of the lightning discharge could be measured remotely. This technology will enable evaluation of the lightning stroke position, but also scientific knowledge regarding the discharge process.

Lightning strokes are mainly measured by electromagnetic antenna. The antenna measurement requires numerous observation points synchronized in time in order to evaluate the lightning stroke position, and lacks flexibility of measurement. On the other hand, radar, an active measurement, has the flexibility of single point measurement, while its use is limited because of legal restrictions on the use of electromagnetic waves. Moreover, its measurement resolution is not high. As an optical remote measurement method, a lidar using the Stark effect has been proposed[1]. Although a fundamental proposal has been reported, it has not yet achieved its ultimate goal.

An in-line type micro pulse lidar (MPL) system has been developed for prediction of disasters resulting from heavy rain and lightning strokes.[2]-[4] The developed MPL has in-line optics which allows a constant overlap of the transmitting and receiving field of views (FOVs). The system can receive the lidar echo from the nearest distance (0m : in front of the system) by using an outgoing annular beam. Futhermore, the optical circulator enables it to separate the transmitting beam and the lidar echo on the coaxial axis. The lidar echo can be separately detected due to its polarization. The lidar can observe ice crystals because of their depolarization effect, and the narrow FOV of 0.1mrad eliminates the depolarization effect caused by multiple scattering. By monitoring the movement of ice crystals, we aim to derive the meteorological parameters connected to heavy rain and lightning strokes, which are causes of local disasters. The in-line type MPL is currently in year-round observation.

However, it is not easy to associate the movement of ice-crystals with local disasters. It is necessary to remove the effects of seasonal change, regional difference, and noisy air current. We aim to grasp the meteorological parameters connected to local disasters more directly with the lidar echo.

The magneto-optical effect (here, Faraday effect) is effective in a partially ionized atmosphere. The polarization plane of the propagating beam will be rotated by the electromagnetic pulse due to the lightning stroke. This study examines the feasibility of optical remote measurement of the change in the electromagnetic field or the ionized density distribution in a high-voltage discharge experiment.

2. Principle

(i) Magneto-optical effect – Faraday effect –

As an initial approach, we considered the contribution of Faraday effect as the magneto-optical effect to the propagating beam. The polarization plane of a beam propagating parallel to the magnetic flux is rotated in a partially ionized atmosphere (plasma) (Fig.1). This effect is known as the Faraday effect. The rotation angle is proportional to the product of the ionization n_e and the magnetic flux density B along the beam propagation path. The linearly polarized beam can be regarded as a combination of the clockwise and the counterclockwise circularly polarized beams. The refractive indices of the ionized atmosphere for each circularly polarized beam are as follows.

$$n_{\pm} = \left(1 - \frac{\omega_{pe}^2}{\omega^2}\frac{\omega}{\omega \pm \omega_{ce}}\right)^{1/2} \qquad \text{---- (1)}$$

$$\omega_{pe} = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}} \qquad \omega_{ce} = \frac{eB}{m_e}$$

where ω_{pe}, ω_{ce} are plasma frequency and cyclotron frequencies, respectively, e is the fundamental charge, m_e is the electron mass, and ε_0 is the permittivity of free space. Therefore, the rotation angle of polarization plane of the beam propagated at distance L (=L_1-L_2) is obtained as follows.

$$\begin{aligned}\delta &= \frac{\pi}{\lambda}\int_{L_1}^{L_2}(n_+ - n_-)dl \qquad \text{----- (2)}\\ &= 2.62\times 10^{-13}\lambda^2\int_{L_1}^{L_2} n_e B dl\end{aligned}$$

where λ is wavelength of the propagating beam.

When the Faraday effect is applied to the lightning measurement, the atmosphere needs to be partially ionized, and the magnetic flux due to the lightning discharge must exist.

(ii) Concept of lightning measurement

Thunderclouds have positive charge at their bases. Cloud-to-cloud discharges occur 4-20 times in a row. It creates electron-ion pairs in the electrically isolated atmosphere/cloud. Each discharge produces such pairs of more than 10^{25} molecules/m^3. That is, the degree of the ionization becomes almost 100% near the discharge path. The discharge current produces an electromagnetic pulse in the atmosphere. When the polarized beam propagates through a partially ionized atmosphere, the polarization planes will be rotated with the Faraday effect. To interact the beam with the lightning discharge, the beam should be propagated at long-distance in the discharge area of high ionization. We assume that such an area is in the cloud base or under the cloud. This configuration is appropriate for lidar measurement, which can scan and monitor a partially ionized atmosphere in a long range. Figure 2 is an illustration of the new type lidar proposed by the authors. The differential detection requires sufficiently high accuracy, which was mentioned in the next section.

The usual lightning discharge generates an electromagnetic pulse in the order of 100μs. As lidar is a time-of-flight measurement, ionization, change of electromagnetic field, and their distribution can be measured as a function of range. The lightning stroke position can be pinpointed with a single lidar base station.

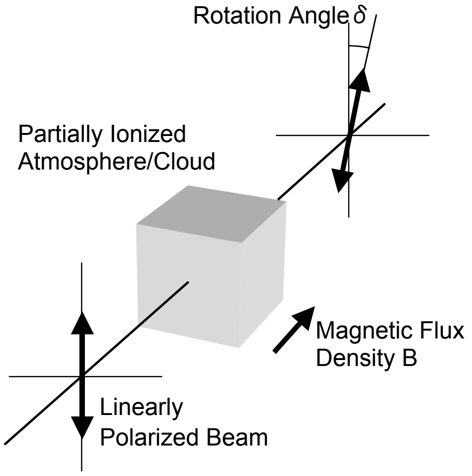


Fig.1 Faraday effect.

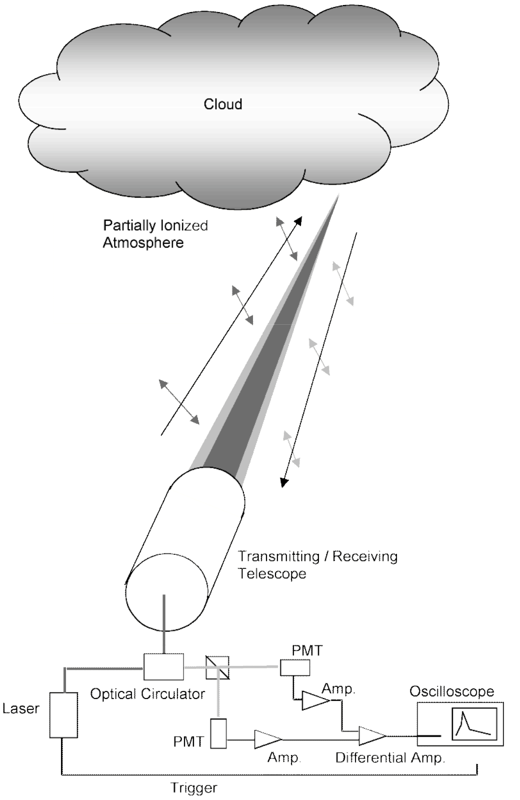


Fig.2 Lidar application of lightning discharge measurement.

3. High-voltage Discharge Experiment

In order to verify whether the change of the polarization plane of a propagating beam due to an electrical discharge can be detected, an experimental apparatus incorporating multiple reflection optics was constructed in the high-voltage discharge equipment.

(i) Optical model

The experimental setup is shown in Fig.3, and the specifications are shown in Table 1. The propagating beam runs repeatedly around the discharge path so that the beam can interact with the high-voltage discharge multiple times, providing enough rotation of the polarization plane due to the faraday effect which can be measured. The optics consists of two parts: an input-output optics part and a square mirror part. The latter is installed inside a discharge chamber. The discharge path is at the center of the square mirror. The polarization and divergence of the beam is adjusted on entering the square mirror. The total length of the optical path can be changed by controlling the tilts of the four sides of the square mirror. The outgoing beam from the square mirror is divided by a polarized beam splitter and detected separately at orthogonal polarizations. The polarization of the incident beam is adjusted to balance the detected intensities. When the discharge occurs in the chamber, the polarization plane rotates, and the difference between the two polarization intensities is detected. In the analysis, the discharge current waveform was defined as that of the lightning return stroke (peak current:2kA)[5]-[7]. The magnetic flux density was calculated with the considerations of the distance from the discharge path and its orientation.

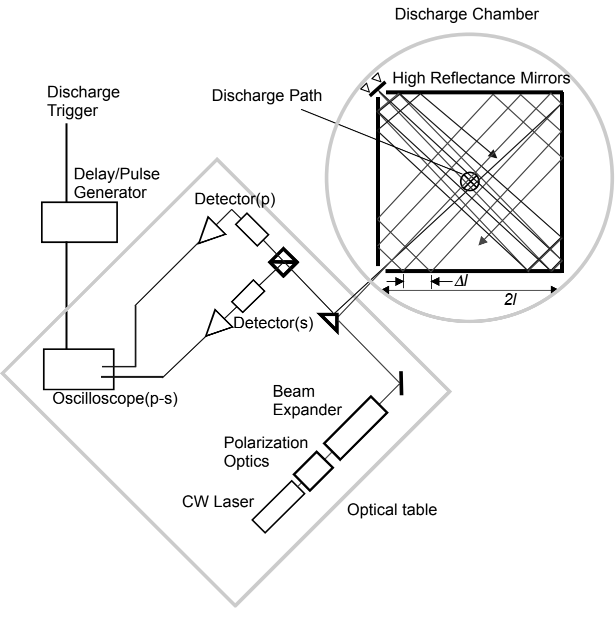


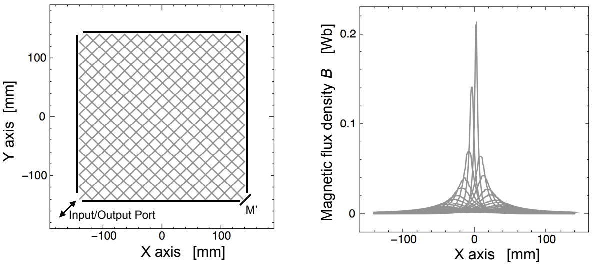
Fig.3 High-voltage discharge experiment.

Table 1. Specification of high voltage discharge experiment.

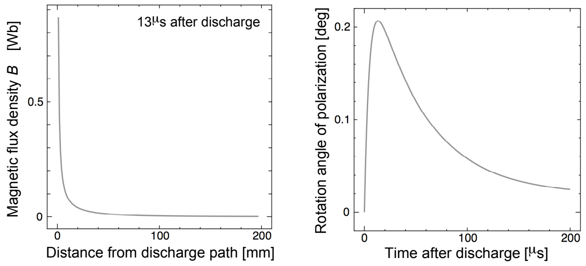
Light source	YAG Laser (λ =532nm) 150mW
Detection	PDs with Amp. + Differential Amplifier
Discharge Gap	5-20cm
Discharge voltage	180kV (max)

(ii) Calculation

Figure 4 shows an example of calculated results. The mirror length was 28cm square. The beam reflection step was 2cm. The propagating beam was reflected multiple times by the four sides of the square mirror, as shown in Fig.4(a). Mirror M' reflects the propagating beam to the output with the return trajectory. The magnetic flux densities projected on a side of the square mirror are shown in Fig.4(b). Multiplying the magnetic flux density B by the electron density n_e along the propagation distance, the rotation angle of the beam polarization palne was estimated by equation (2). Figure 4(c) shows the change of the magnetic flux density with respect to the distance from the discharge path. The flux density changes its value along the elapsed time. The magnetic flux density B is inversely proportional to the distance from the discharge path. The electron density n_e is high only in the discharge path. We assumed that it was $10^{25}/\mathrm{m}^2$ within 2cmϕ in the discharge path. As a result of the calculation of (a)-(c), the rotation angle of the polarization plane was estimated as shown in Fig.4(d). The change of the rotation angle was the same response time as the discharge current. The result shows that the frequency response of a few MHz was sufficient for the detector. Other calculations with different discharge and the beam propagation conditions are summarized in Table 2. Selecting those conditions, we can distinguish the rotation angle of the beam polarization plane by differential detection with a dynamic range of 30dB (See polarization ratio of Table 2).



(a) Optical path (b) Magnetic flux density B



(c) B vs distance (d) Rotation angle

Fig. 4 Calculated results under high-voltage discharge experiment.

Table 2. Estimation of rotation angle of beam polarization under various conditions.

Mirror Length [mm]	Number of reflections / step [mm]	Necessary reflectance [%]	Total optical path length [m]	Discharge Gap [cm]	Rotation Angle (Max) [deg.]	Polarization Ratio
280	12 / 21.4	91	9.5	10	0.21	1:1.007 (21dB)
280	28 / 10.0	96	22.2	10	0.51	1:1.018 (18dB)
280	56 / 5.0	98	44.3	10	0.95	1:1.034 (15dB)
500	12 / 41.7	91	17.0	10	0.074	1:1.003 (26dB)
500	50 / 10.0	98.3	70.7	10	0.51	1:1.018 (18dB)
500	12 / 41.7	91	17.0	20	0.074	1:1.003 (26dB)
500	50 / 10.0	98.3	70.7	20	0.52	1:1.018 (17dB)

(iii) Experimental Setup

The experimental setup of Fig.3 was constructed and installed in the high-voltage discharge equipment. Figure 5 shows snapshots of the optics and the square mirror in the discharge chamber. The sides of the square were 28cm in length, and its reflectance was about 95%. The number of the reflections on a single mirror was 12-14. The total round-trip optical path length is 20m. The incident laser beam power of 150mW was attenuated to less than 100μW because of the reflection loss of the mirrors and divergence of the beam. The rotation angle of the beam polarization was estimated as 0.21 degrees (max) in the above situation, so the polarization ratio will become 1:1.007. It means that the differential detection of the dynamic range of 30dB enables to distinguish the difference.

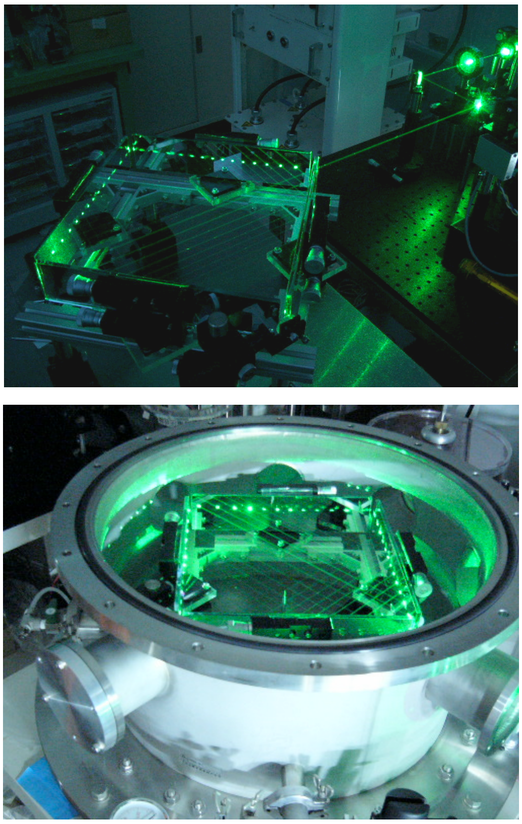


Fig.5 Experimental optics and square mirror.

4. Summary

The rotation in the polarization plane of a beam propagating through a region of high-voltage discharge was estimated. To extend the optical path length in the vicinity of the discharge, repeating mirror optics was devised. The experimental setup was installed in a discharge chamber.

Rotation angle measurement of the propagating beam polarization plane utilizing the Faraday effect can be applied to lidar measurement of lightning discharges. As the pulse beam enables time-resolved detection, evaluation of the lightning stroke position, measurement of the change in the electromagnetic field and spatial distribution of ionization should be possible.

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