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Propagation characteristics of laser light in drizzle-like mist

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***Abstract*—Quantum illumination is a target detection technology that utilizes the quantum entangled state of light. We are conducting research on applying two-mode squeezed light to quantum illumination. In quantum illumination, one light wave in a quantum entangled state is irradiated toward a target in atmospheric disturbance. Therefore, it is important to investigate the propagation characteristics of light waves during atmospheric disturbances towards quantum illumination. As an atmospheric disturbance, we focused on drizzle, which is a factor that obstructs visibility. In this study, we first created a mist room that generates drizzle-like mist. Subsequently, the effect of the mist on the light wave was investigated by propagating the laser beam in the mist space.**

I. Introduction

Quantum illumination is a target detection technology that utilizes the quantum entangled state of light [1], [2], [3]. Due to the non-classical characteristics of the light source, it is possible to improve the detection sensitivity of the target. It is also expected that the error probability when detecting a target will be improved even under the influence of atmospheric disturbance such as loss and noise. Initially, entangled photon pairs were proposed as entangled light sources [1]. Later, Tan, *et al*. proposed a Gaussian state such as a two-mode squeezed vacuum state with macroscopic quantum entanglement as a light source [2]. They showed that under certain conditions, the two-mode Gaussian state has better target detection performance than the single-mode laser.

We are studying quantum illumination using two-mode squeezed light [4]. In addition to developing quantum light sources, we have also begun to study the propagation characteristics of light waves in atmospheric disturbances in recent years [5], [6], [7]. When detecting a target in a disturbance by quantum illumination, it is necessary to know the basic propagation characteristics of light waves in advance. As an example of atmospheric disturbance, we focused on the effect of fog, which is a major factor obstructing visibility. In previous studies, we have investigated the propagation characteristics of visible/near-infrared wavelength laser beams in fog. A fog is a collection of water particles of 5 μm to 50 μm floating in the air. The interaction of fog with visible and near-infrared light is classified as Mie scattering [8], [9]. As a result of experiments using an optical interferometer, it was found that the effect of uniform fog on the propagation of light waves is mainly the attenuation of energy.

In this study, we focused on the propagation characteristics of the laser beam in drizzle. Drizzle is meteorologically fine rain with a raindrop diameter of less than 500 μm and is also a factor that obstructs visibility. The interaction between drizzle and visible/near-infrared light is considered to be both Mie scattering and geometrical optics [8], [9]. In addition to energy attenuation, there is concern about beam distortion due to effects such as refraction. Therefore, it is important to investigate the propagation characteristics of light waves in drizzle for the study of quantum illumination. However, it is difficult to carry out experiments using natural drizzle in a laboratory environment. In this research, first of all, we made a mist room to make mist-like drizzle fall outdoors using tap water. Next, the laser beam was propagated in a mist space 10 meters long, and the energy attenuation and the change in the beam profile were measured.

II. Outline of experimental equipment

Fig. 1 shows an experimental setup for examining the propagation characteristics of laser light in the mist space. Fig.(a) is a top view and (b) is a side view. A hose to which 12 spray nozzles (Kohnan shoji, LFX09-9576) for generating mist were connected was installed at a height of 2.2 meters. By running tap water through the hose, a drizzle-like mist was applied to an area with a total length of 5 meters and a width of 0.6 meters. In order to prevent water from splashing around, a waterproof curtain was used to enclose the space where the mist fell. The particle size of the mist is several hundred μm, which seems to be sufficiently close to that of natural drizzle.

A continuous wave He-Ne laser with a wavelength of 633 nm was used as the light source for the optical experiment. The laser light intensity was 5 mW. The size of the laser beam was expanded to about 3.5 mm by using the lens 1 (L_1) and the lens 2 (L_2) having focal lengths of 10 cm and 50 cm, respectively. The laser beam was reflected by mirrors (Ms) and makes a round trip in the mist room. As a result, the laser beam propagates in a mist space with a total length of 10 meters. Optical components such as laser and mirrors were fixed to metal plates. The transmission intensity of the laser beam propagating through the mist room was

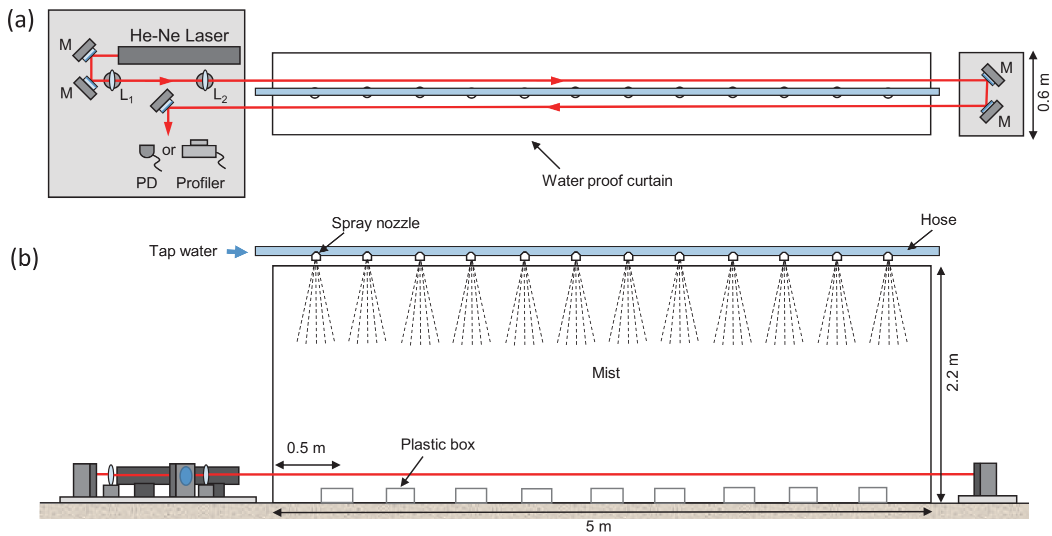

Fig. 1. Experimental setup for examining the propagation characteristics of laser light in mist space. (a) Top view, (b) Side view.

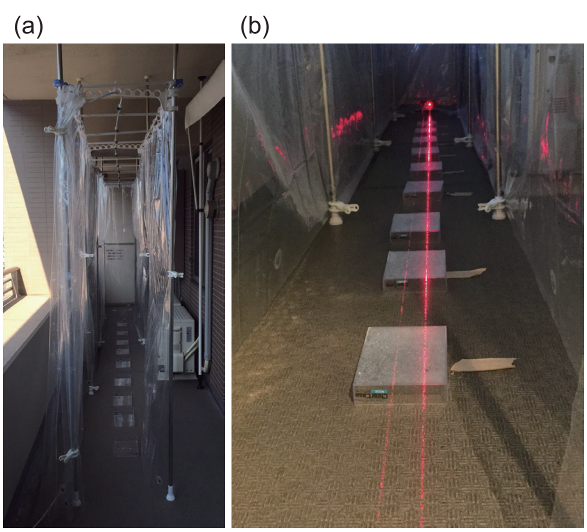

Fig. 2. Photo of Mist room. (a) Front appearance. (b) Laser light scattered by mist.

measured with a photodetector (PD). The spatial mode of the laser beam was also measured using a beam profiler.

Fig. 2 (a) shows the appearance of the mist room as seen from the laser emitting side. Further, Fig. 2 (b) shows the laser light propagating in the mist space. It can be clearly seen that the laser light is scattered by the water particles of the mist.

III. Experimental results

Fig. 3 shows the distribution of mist precipitation generated in the mist room. Nine plastic boxes are installed every 0.5 meters in the mist room. The horizontal axis represents the position of the box. The vertical axis shows the amount of precipitation per unit time estimated from the amount of water accumulated in each box in 30 minutes. By changing the water pressure of the tap, the amount of precipitation of mist generated from the spray nozzle can be changed. From Tests 1 to 3, three types of precipitation distribution were measured. The mean values of precipitation at 9 locations in each test were 6.6 [mm], 10.6 [mm], and 13.8 [mm] per unit time. In all measurements, precipitation tended to be high near the tap. From these results, the standard deviations of precipitation at each position were 2.1 [mm], 3.1 [mm], and 3.8 [mm] for Tests 1 to 3, respectively. In the mist room produced this time, the uniformity of precipitation is still insufficient and needs to be improved in the future.

Next, the laser beam was propagated in the mist space, and the effect of energy attenuation due to the mist was investigated. First, the transmitted light intensity of the laser beam was measured, and the transmittance T in the mist space was measured. Energy attenuation is calculated by $1-T$. Fig. 4 shows the measurement results of precipitation and attenuation. Precipitation error bars correspond to the magnitude of the standard deviation derived from the results of Fig. 3. From this result, it is clear that the energy of the laser beam is attenuated as the precipitation increases. It is considered that the laser beam lost a part of its energy due to the influence of Mie scattering by the mist.

Subsequently, the intensity distribution of the laser beam was observed using a beam profiler (Ophir, BM-USB-SP928-OSI). Fig. 5 shows the observation results when mist is not generated. The shape of the intensity distribution was almost circular, and the intensity profile in the vertical and horizontal directions was almost Gaussian distribution. When the laser beam propagated

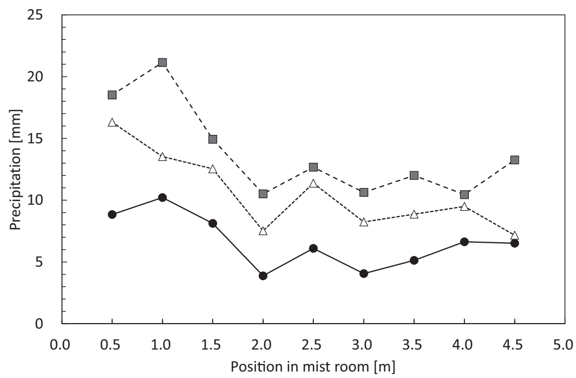

Fig. 3. Measurement result of precipitation distribution in Mist room. The black circle is the result of test 1, the white triangle is the result of test 2, and the black square is the result of test 3. In each test, the amount of precipitation of mist was changed by adjusting the tightness of the tap water valve. The left side of the graph is closer to the tap water valve.

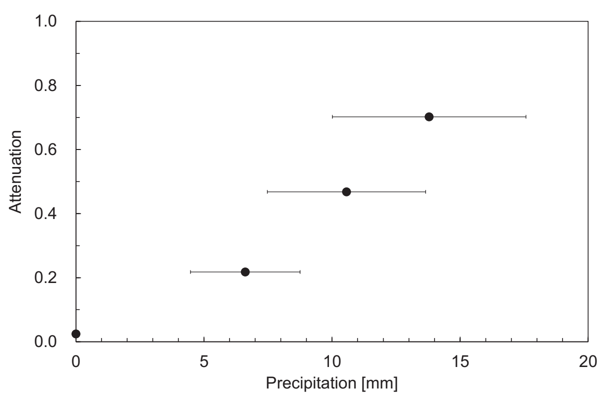

Fig. 4. Results of measurement on the relationship between mist precipitation and energy attenuation of laser light.

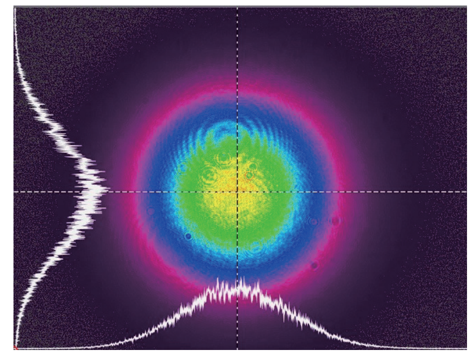

Fig. 5. Observation result of the beam profile of the laser beam when mist is not generated. The vertical and horizontal intensity profiles are well approximated by the Gaussian distribution. The active area of the beam profiler is 5.3 mm × 7.1 mm.

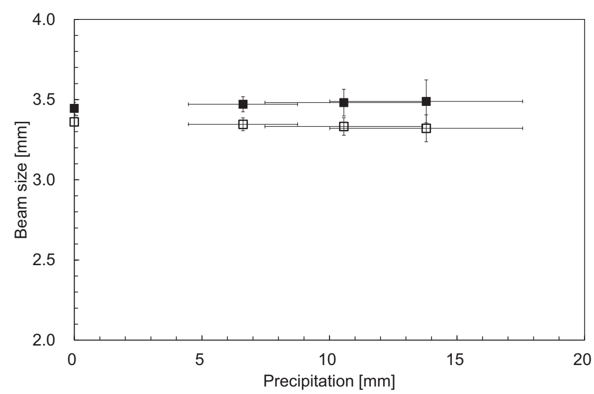

Fig. 6. Measurement results of mist precipitation and beam size. The black square and the white square are the beam sizes in the horizontal and vertical axes, respectively.

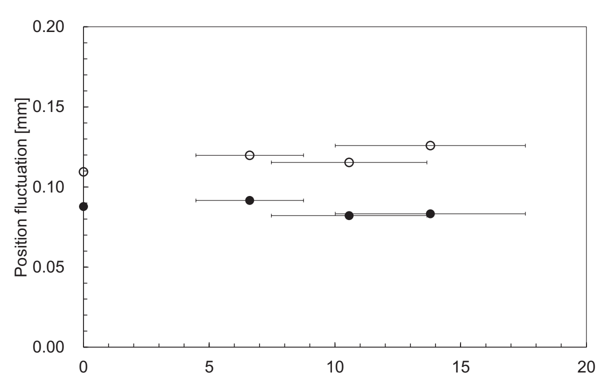

Fig. 7. Measurements of mist precipitation and centroid fluctuations in the beam profile. The black and white circles are the results in the horizontal and vertical axes of the beam profile, respectively.

in the mist space, this intensity distribution was almost unchanged, and no beam distortion was observed.

Fig. 6 shows the measurement result of the beam size when the precipitation of mist is changed. When measuring the beam size, the average for 500 frames was calculated. The error bars of beam size at each measurement point correspond to the standard deviation. The average value of the beam size did not change even if the amount of mist precipitation increased. From this result, it is considered that the mist does not affect the spatial mode of the laser beam so much. However, as the amount of mist precipitation increased, the fluctuation of beam size, that is, the standard deviation, tended to increase. Fig. 7 shows the standard deviation of centroids in the beam profile when the amount of mist precipitation is changed. Since the fluctuation of the centroid is almost constant, it is considered that the mist has almost no effect on the pointing stability of the laser beam.

From the above measurement results, it was found that the effects of drizzle-like mist on the propagation of laser light are mainly energy attenuation and fluctuation of beam size. The effect on beam profile and pointing stability is negligible.

IV. Summary

For the study of quantum illumination, it is important to investigate the propagation characteristics of light waves during atmospheric disturbances. We focused on the effects of drizzle as an example of atmospheric disturbances and investigated the effects on the propagation characteristics of laser light. In this study, we first created a mist room that generates drizzle-like mist using tap water. The amount of mist precipitation in the mist room was not uniform. In the future, it is necessary to improve the uniformity of precipitation. Subsequently, the propagation characteristics of light waves in the mist space were investigated using He-Ne laser light. As a result, the energy attenuation of the light wave and the fluctuation of the beam size were observed due to the influence of the mist. No beam profile distortion or beam pointing fluctuations were observed. In the future, we are studying more detailed analysis by conducting light interference experiments in a drizzle-like mist space.

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