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A study of laser beam propagation through 10 meters length a fog

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***Abstract*—Quantum illumination utilizing two-mode squeezed light beams is a prospective target detection technique. Because of non-classicality of the light source, the improved error probability of target discrimination is expected even in a lossy optical medium. In such technique one of the entangled beams, a signal beam, is reflected by a target in a lossy optical medium and then detected at the homodyne receiver. To realize high detection efficiency it is important to efficiently generate the optical interference between the signal and local oscillator beams. In previous our work, the author focused on a fog as a probable optical loss and studied laser beam interference propagating through 60 cm length of an uniform fog utilizing Mach-Zehnder interferometer. In this work we continue to study the effect of a fog on the laser beam's interference by extending the length of the fog up to 10 meters. The experimental results show that the effect of the uniform fog up to 10 meters length is mainly the optical energy loss.**

I. Introduction

Quantum illumination is a target detection technique utilizing quantum entangled states of light [1], [2], [3]. Two-mode squeezed light beams are a prospective light source for realizing quantum illumination [4]. In quantum illumination with them, one of the entangled light beams usually called as a signal beam is transmitted to the target through a lossy optical medium or noisy environment and reaches the receiver. The other beam usually called as a reference beam is directly sent to the receiver with a lossless channel. At the receiver the target detection is attained through measuring non-classical correlation between both beams by balanced homodyne detection. Because of the non-classical correlation of the light source, it is expected that the error probability of discrimination for target presence or absence is improved even in a lossy or noisy environment.

In actual target detection with quantum illumination, the author thinks that a fog is a serious problem as a probable optical loss. Fog is a random medium consisting of water particles with diameter from about 5 μm to 50 μm [5]. The interaction between a fog and visible or near-infrared light is classified as Mie scattering. So, the fog causes an optical energy loss or spread of a light beam due to Mie scattering [6]. In such a condition it is difficult to achieve efficient homodyne detection, since the optical signal is generated by interference between the signal and local oscillator beams. The energy loss of the signal beam directly reduces the homodyne detection signal. On top of that the spread of the signal beam causes its spatial-mode distortion and insufficient mode matching with the local oscillator beam. So, it is important to study a fundamental property of the light beam's propagation in a fog.

In previous work the author studied propagation characteristics of a laser beam through a foggy atmosphere using a Mach-Zehnder interferometer [7]. A fog chamber was installed in one of the optical path of the interferometer. And visibility of the interferometer was observed at various optical losses by changing the density of uniform fog. The experimental result shows that the effect of the fog is mainly the optical energy loss. However the optical length in the fog chamber was limited at 60 cm in previous work [7]. In such a condition there is a possibility that the author could not detect the effect of the beam spread or spatial-mode distortion. Moreover it is required that the signal beam is propagated through some hundreds of meters of a foggy atmosphere in actual target detection. So, we continue the previous work and extend the optical path length in a foggy atmosphere to learn more precisely about its effect on the laser beam. In this work we study the optical interference propagating through 10 m length of a fog using Mach-Zehnder interferometer.

II. Experimental setup to observe laser beams interference through a foggy atmosphere

Fig. 1 shows the Mach-Zehnder interferometer to observe the optical interference propagating through 10 meters length of a foggy atmosphere. A continuous wave He-Ne laser with a liner polarization and wavelength of 632.8 nm was used as a light source. The incident beam has about 1 mm in diameter and is divided in two beams by beam splitter BS_1. One is the signal beam and we call the other one local oscillator beam LO for analogizing the optical configuration of homodyne detection. Both beams are expanded to 5 mm in diameter by using spherical lenses f_1 with a focusing length of 10 cm and f_2 , f_3 with a focusing length of 50 cm. The signal beam is introduced into the fog chamber made of an acrylic box with 1.25 m of length, 0.5 m of width and 0.6 m of height. The signal beam makes 4 times of round trips inside the chamber with mirrors located outside. It results 10 m length of signal beam's propagation in the fog chamber. The entrance and exit apertures of the chamber for the

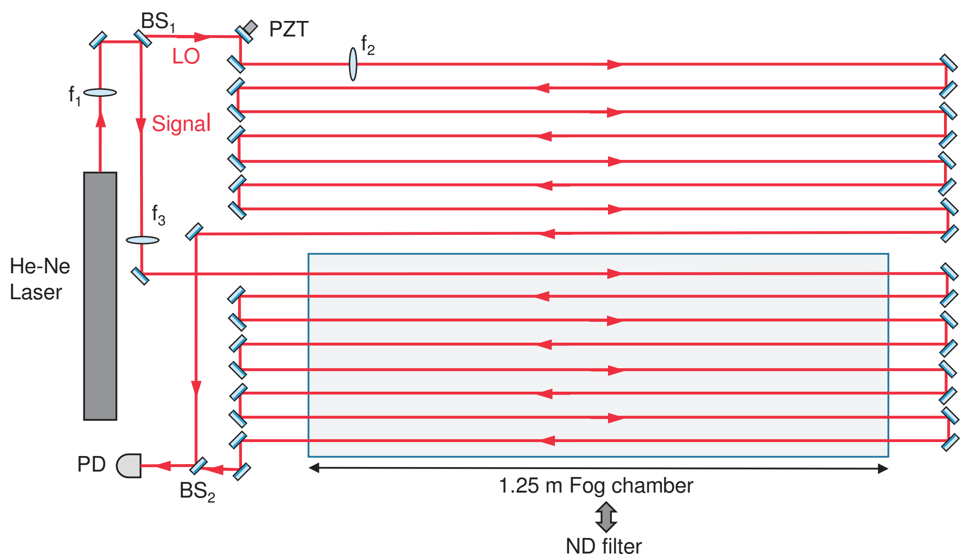

Fig. 1. Schematic view of Mach-Zehnder interferometer. The signal beam makes 4 round trips through the chamber which yields 10 m length of a foggy atmosphere. On the other hand local oscillator beam LO propagates in a free space. Both beams are combined with beam splitter BS_2 and the optical interference signal is detected by photo-detector PD. In this work the fog chamber was replaced by the neutral density (ND) filter to study the effect of just energy loss on the laser beam interference.

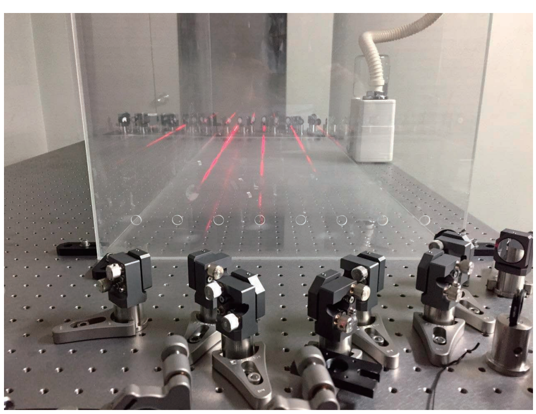

Fig. 2. Photograph of the fog chamber installed in the optical path of the signal beam.

signal beam are just through holes with 1.2 cm diameter to avoid the light attenuation or scattering caused by dew condensation. The local oscillator beam LO propagates in a free space and has the similar optical configuration with the signal beam to achieve the same optical length to generate efficient optical interference. One reflective mirror is attached to piezo transducer PZT driven with a triangle voltage wave with 40 Hz generated by a function generator. It yields modulation of a relative optical phase between signal and LO beams. Finaly the signal and LO beams are combined by beam splitter BS_2 to generate the optical interference. The optical interference signal was detected by photo-detector PD and monitored by a digital oscilloscope.

Fog is artificially generated using ultrasonic atomizer unit (JM-200, Honda electronics, Co., LTD.) and introduced into the chamber with a duct hose which is not shown in Fig. 1. The ultrasonic transducer is tuned at 2.4 MHz and to generate water particles with 3 μm in diameter. Firstly the highly dense fog was uniformly distributed inside the chamber. It took several minutes before the fog completely disappears. The laser beam interference was observed several times until the fog was disappeared, since there is not control function of the fog density with the chamber. Fig. 2 shows an outer view of the fog chamber seen from the entrance side. It is obvious that significant Mie scattering from the signal beam is seen when the fog density is rather high. The transmittance of the signal beam was also monitored to evaluate optical energy loss L caused by the fog.

In this work the fog chamber was replaced with a neutral density (ND) filter and then the optical interference was observed. In this optical configuration the signal beam is affected only by an energy loss and does not cause beam spread.

III. Experimental Results and Discussions

Fig. 3 shows the results of visibility measurements from the optical interference signals. The horizontal axis is optical energy loss L and the vertical axis is the visibility. To evaluate the optical energy loss L, firstly transmittance T of the signal beam through the fog chamber or ND filter is measured and then calculated with the relation of $L = 1 - T$. Solid circles are results with the effect of fog. Measurements of the interference signal were repeated by changing the fog density which is related with optical energy loss L. Open squares are results with the ND filter instead of the fog chamber. The ND filter only affects the optical energy loss of the

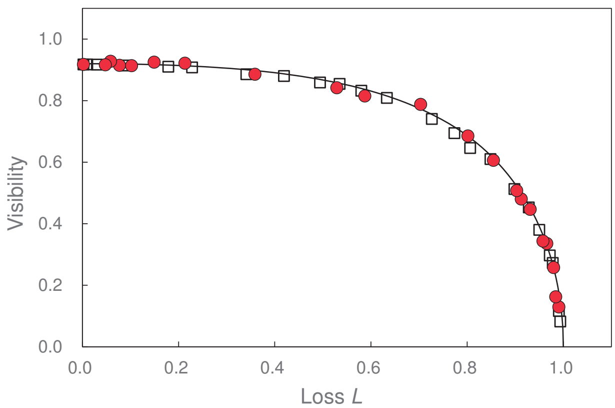

Fig. 3. Results of visibility measurement and calculation results. Open squares are experimental results using a neutral density (ND) filter instead of the fog chamber. Solid circles are experimental results with the signal beam propagating through 10 m length of a foggy atmosphere. Solid curve is calculation results assuming only the optical energy loss L.

signal beam. Under ideal condition the visibility at L=0 is 1, however it is limited at 0.92. It may be caused by imperfection of the optical alignment or quality of reflective mirrors. This initial imperfection is thought as constant while the experiment as long as only the optical energy loss L is changed. Solid curve is calculation results of the visibility with Eq.(1) used in previous work [7]

$$V(L) = V_0 \frac{\sqrt{1-L}}{1-\frac{L}{2}}. \tag{1}$$

where only the optical energy loss L is changed. Assuming the effect of imperfection is constant, the equation is multiplied by the initial imperfect visibility V_0 which is kept at 0.92. It is noticeable that the visibility with the effect of the fog agrees well with both the experimental results using the ND filter and calculation results. The effects of beam spread or spatial-mode distortion may cause the reduction of visibility values from the calculation results with Eq.(1). However these effects are small or negligible small, as long as the laser beam interference was measured using the uniform fog. From these results we can conclude that the effect of the uniform fog up to 10 meters length is mainly the optical energy loss.

In the actual quantum illumination, the signal beam propagates through a foggy atmosphere, reflected by a target, and is mixed with a local oscillator beam for homodyne detection. To achieve high homodyne detection efficiency, the high visibility between the signal and LO beam is preferred. Our result shows that the uniform fog does not cause beam spread and then additional degradation of the visibility between both beams. We only have to consider the effect of optical energy loss as long as the fog is uniform.

IV. Summary

Quantum illumination utilizing two-mode squeezed light beams is a prospective target detection technique. Because of its non-classical property it is expected that the error probability of target discrimination is improved even in a lossy optical medium. To investigate the homodyne detection efficiency at the receiver, it is important to study optical beam propagation characteristics at various optical loss conditions. In this work we focused on a fog as a probable optical loss toward the actual target detection and studied laser beam interference propagating through it utilizing Mach-Zehnder interferometer. The laser beam interference was observed even after the signal beam propagated through the uniform fog up to 10 meters length. Visibility of the interferometer was measured at various optical losses by changing the fog density. The experimental results show good agreement with results using the neutral density filter and calculation results assuming only the effect of an energy loss. From these results we can conclude that the effect of the uniform fog up to 10 meters length is mainly the optical energy loss. The beam spread or spatial mode distortion was small or negligible small in the current study.

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