ISSN 2186-6570

Laser beam interference propagating through a foggy atmosphere

Genta Masada

Quantum ICT Research Institute, Tamagawa University
6-1-1 Tamagawa-gakuen, Machida, Tokyo 194-8610, Japan

Tamagawa University Quantum ICT Research Institute Bulletin, Vol.8, No.1, 31-34, 2018

Tamagawa University Quantum ICT Research Institute Bulletin
Vol.8 No.1 : 31−34（2018）

Laser beam interference propagating through a foggy atmosphere

Genta Masada
Quantum ICT Research Institute, Tamagawa University
6-1-1 Tamagawa-gakuen, Machida, Tokyo 194-8610, Japan
E-mail: g.masada@lab.tamagawa.ac.jp

***Abstract*—Quantum illumination utilizing two-mode squeezed light beams is a prospective target detection technique. Because of a non-classical property of the light source it is expected that the error probability of target discrimination is improved even in a lossy optical medium. At the receiver one of the entangled beams, a signal beam, transmitted to the target through a lossy optical medium is detected by balanced homodyne measurement. To realize high detection efficiency it is important to generate efficiently the interference between the signal and local oscillator beams. In this work we focused on a fog as a probable optical loss and studied laser beam interference propagating through it utilizing Mach-Zehnder interferometer toward quantum illumination receiver. Laser beam interference was observed after one of the laser beam propagated through the fog. Visibility of the interferometer was measured at various optical losses by changing the fog density.**

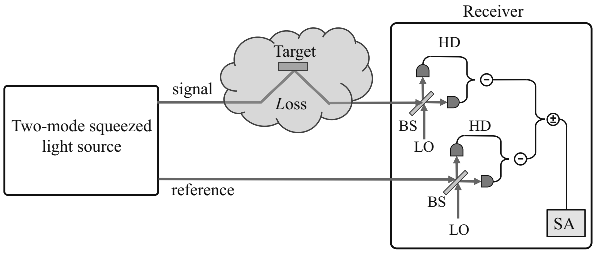

Fig. 1. Optical model of quantum illumination using a two-mode squeezed light source. The signal beam is send to the target through a lossy optical medium and reaches to the receiver. The reference beam is sent to the receiver with a lossless channel. At the receiver non-classical correlaition between the signal beam degraded by the optical loss and the reference beam is measured and the target detection is attained.

I. INTRODUCTION

Quantum illumination is a target detection technique utilizing quantum entangled states of light [1], [2], [3]. 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. It is expected that the error probability of discrimination for target presence or absence is improved even in lossy and noisy environments because of the non-classical correlation. Initially a pair of entangled photons was proposed as a quantum entanglement resource [1]. After that, Tan, *et al*. proposed entangled two-mode Gaussian states such as two-mode squeezed vacuum states as a light source. They show that two-mode Gaussian states have better target-detection property compared with a single-mode laser [2]. Motivated by these works the author recently started a research to apply two-mode squeezed light beams to the quantum illumination experiment [4].

In quantum illumination with two-mode squeezed light beams, the signal and reference beams are measured by balanced homodyne detection, respectively, at the receiver. Difficulty of quantum illumination is to detect the optical interference between the signal beam degraded by an optical loss and the local oscillator beam at the receiver. In this work we are thinking about a foggy atmosphere as a probable optical loss in actual target detection. A fog affects on the propagation property of light beams through the optical scattering. So, it is important to study a fundamental property of light beams propagating in a fog. In this work we observed interference of laser light beams affected by a uniform fog as a preliminary experiment for the receiver of quantum illumination.

II. OUTLINE OF QUANTUM ILLUMINATION WITH A TWO-MODE SQUEEZED LIGHT SOURCE

Fig. 1 shows a schematic of quantum illumination with a two-mode squeezed light source. Firstly entangled two-mode squeezed light beams are generated. One of the entangled beams usually called as a signal beam is send to the target through a lossy optical medium and reaches to the receiver. Another beam called as a reference beam is send directly to the receiver using a lossless optical channel. At the receiver non-classical correlation between both beams is measured by homodyne detectors HDs to attain target detection. Local oscillator beams LOs for homodyne measurement are also sent to the receiver with a loss less channel. The sum and subtraction signals from homodyne detectors HDs are monitored by spectrum analyzer SA and used to check the non-classical correlation between both beams [5], [6].

In this work we are focusing on a foggy atmosphere as a probable optical loss in the case of quantum illumination. Fog is a random medium consisting of water particles with diameter from about 5 μm to 50 μm [7].

The interaction between a fog and visible or near-infrared light is classified as Mie scattering. The fog causes an energy loss and spread of optical beams through Mie scattering [8]. Difficulty of quantum illumination is to detect the degraded signal beam by homodyne measurement, since it is required to generate the interference signal by mixing with a local oscillator beam. The energy loss of the signal beam directly reduces the homodyne measurement signal. On top of that the spreading of the signal beam causes its spatial-mode distortion and insufficient mode matching with the local oscilaltor beam. As a result it may causes reduction of the homodyne detection efficiency and therefore the performance of target detection. So, it is important to study how the fog affects on the interference signal toward quantum illumination receiver. However, it is rather complicated experiment to study directly the effect of the fog on squeezed light beams. As a preliminary experiment we study the effect of the fog on laser beam interference using Mach-Zehnder interferometer.

III. EXPERIMENTAL SETUP TO OBSERVE LASER INTERFERENCE THROUGH A FOG

Fig. 2 shows the experimental setup of Mach-Zehnder interferometer to observe laser beam interference. A continuous wave He-Ne laser with wavelength at 632.8 nm was used for the light source. Polarization of the light beam is linearl in horizontal axis. Firstly the incident laser beam is divided in two beams by beam splitter BS_1. One is the signal beam and we call other one local oscillator beam LO for descriptive purposes to compare with the optical configuration of homodyne measurement as shown in Fig. 1. The signal beam passes through the fog chamber made of an acrylic box with 60 cm of length, 30 cm of width and 15 cm of height. The 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. 2. The ultrasonic transducer is tuned at 2.4 MHz and to generate water particles with 3 μm in diameter. The entrance and exit apertures of the chamber for the signal beam are just through holes with 1 cm diameter to avoid the light attenuation or scattering caused by dew condensation. On the optical path for the LO beam, reflective mirror M with piezo transducer PZT was used for modulating relative optical phase between signal and LO beams. Finally the signal and LO beams are combined by another beam splitter BS_2 to observe the interference signal with photodetector PD.

At this moment there is not control function of the fog density in the chamber. We firstly waited a few minutes before the fog became uniformly distributed inside the chamber. It took several minutes before the fog completely disappeared. So, we observed laser beam interference before the fog is disappeared and simultaneously monitored the transmittance of the signal beam which is related with the fog density in each case.

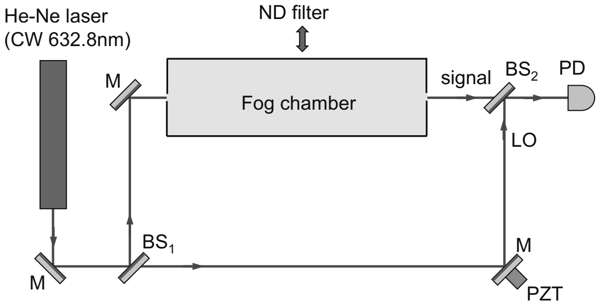

Fig. 2. Schematic view of Mach-Zehnder interferometer. The signal beam passes through the fog chamber. The local oscillator beam LO passes through another loss less path. Both beam are combined with beam splitter BS_2 and the interference signal is detected by photodiode PD. In this work the fog chamber was replaced with the neutral density ND filter to study the effect of just energy loss on the laser beam interference.

In this work the laser beam interference was observed also with a neutral density (ND) filter instead of the fog chamber. In this optical configuration the signal beam is affected only by an energy loss and not affected by beam spreading.

IV. THEORETICAL FORMULA OF LASER BEAM INTEREFRENCE THROUGH A LOSSY MEDIUM

Firstly we introduce a theoretical formula of laser beam interference propagating through a lossy optical medium. For the first approximation we only assume the effect of an energy loss and don't take into account of beam spread or spatial-mode distortion of the signal beam in this model . The incident laser light beam with intensity I is divided in signal and local oscillator LO beams with the intensity of I_s and I_{LO} by first beam splitter BS_1. The laser beam intensity satisfies following relation before and after the beam splitter BS_1,

$$I = I_s + I_{LO}. \tag{1}$$

Only the signal beam passes through a lossy optical medium and affected by an energy loss. After that the signal beam is mixed with the LO beam by beam splitter BS_2 with 0.5 of transmittance. The intensity of the interference signal $I(\phi, L)$ between the signal and LO beams is gives by

$$I(\phi, L) = \frac{1}{2} I_s(1-L) + \frac{1}{2} I_{LO} + \sqrt{I_s I_{LO}(I-L)} \cos(\phi) \tag{2}$$

where L is the energy loss of the signal beam and ϕ is the relative optical phase between both beams. In the case that first beam splitter BS_1 has 0.5 of transmittance, the intensity of signal and LO beams are same and given as

$$I_s = I_{LO} = \frac{I}{2}, \tag{3}$$

respectively. Then the description of the interference signal is simplifies as

$$I(\phi, L) = \frac{I}{2}(1 - \frac{L}{2}) + \frac{I}{2}\sqrt{I - L}\cos(\phi) \qquad (4)$$

The maximum and minimum values of the interference signals $I(L)_{max}$ and $I(L)_{min}$ at given optical loss L are obtained at the phase is 0 and π, and described as

$$I(L)_{max} = \frac{I}{2}(1 - \frac{L}{2}) + \frac{I}{2}\sqrt{I - L} \qquad (5)$$

and

$$I(L)_{max} = \frac{I}{2}(1 - \frac{L}{2}) - \frac{I}{2}\sqrt{I - L}, \qquad (6)$$

respectively. Visibility of the interference signal affected by optical loss L is calculated by following equation

$$V(L) = \frac{I(L)_{max} - I(L)_{min}}{I(L)_{max} + I(L)_{min}}. \qquad (7)$$

Using the maximum and minimum intensity, $I(L)_{max}$ and $I(L)_{min}$, visibility $V(L)$ is given by

$$V(L) = \frac{\sqrt{1 - L}}{1 - \frac{L}{2}}. \qquad (8)$$

V. EXPERIMENTAL RESULTS AND DISCUSSIONS

Firstly the inner view of the fog chamber was observed by a digital camera by changing the fog density. Simultaneously, transmittance T of the chamber which is related with the fog density was detected by passing He-Ne laser light beam through it. Optical loss L of the chamber is given by transmittance T with the equation of $L = 1 - T$. Fig. 3 shows the views inside the fog chamber from the side of laser beam entrance with optical losses (a) L=0.00, (b) L=0.50, (c) L=0.90, and (d) L=0.99, respectively. The number on plates is showing distance from the laser beam entrance. It is obvious that the range of view is getting worse with increasing optical loss L. Notice that significant Mie scattering of the laser light beam is clearly observed when the optical loss L is rather high.

Fig. 4 shows measurement results of interference signals of the Mach-Zehnder interferometer. Signal beam is passing through the fog chamber with optical losses (a) L=0.00, (b) L=0.50, (c) L=0.90, and (d) L=0.99, respectively. The horizontal axis represents time which is equivalent to the relative optical phase ϕ between the signal and LO beams. The vertical axis is intensity I of laser interference signal detected by photo-detector PD. It is obvious that the fringe contrast corresponding to the difference between maximum and minimum intensity, $I(L)_{max}$ and $I(L)_{min}$, is getting small by increasing optical loss L.

By changing the fog density which is related with optical loss L, measurements of the interference signal were repeated. Fig. 5 shows the visibility calculated with observed maximum and minimum intensity, $I(L)_{max}$ and $I(L)_{min}$, of the interference signal. The horizontal axis is optical loss L and the vertical axis is the visibility. Solid circles are results with the effect of the fog. Open diamonds are results with a neutral density ND filter instead of the fog chamber. The ND filter exerts only the energy-loss influence on the signal beam. Solid curve is calculation results of the visibility assuming only the energy loss L using Eq.(8). It is noticeable that the visibility with the effect of the fog agrees well with both the experimental results with the ND 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 is mainly the energy loss. This time we could not detect the significant effects of beam spread or spatial-mode distortion which may cause degradation of the mode matching between two beams and then yield the reduction of the visibility from the calculated values with Eq.(8). These effects were small or negligible small, as long as the laser beam interference was measured using the fog chamber. In the quantum illuminaiton experiment the signal beam which propagates through a foggy atmosphere is mixed with a local ascillator beam for homodyne measurement. In this case high visibility between the signal and local oscillator beam is preferred to achieve high homodyne-detection efficiency. Our result shows that the uniform fog does not degrade the mode matching between both beams.

VI. SUMMARY

Quantum illumination utilizing two-mode squeezed light beams is a prospective target detection technique. It is expected that the error probability of target discrimination is improved even in a lossy optical medium because of its non-classical property. To investigate high detection efficiency at the receiver it is important to study optical beam interfernce at various optical-loss conditions. In this work we focused on a fog as a probable optical loss in actual target detection and studied laser beam interfernce propagating through it utilizing Mach-Zehnder interferometer toward the quantum illumination receiver. The laser beam interference was observed even after the signal beam propagated through the fog chamber. Visibility of the interferometer was observed at various optical losses by changing the fog density. The experimental results show good agreement with both experimental results with 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 is mainly the energy loss. The beam spread or spatial-mode distortion was small or negligible small, as long as the laser beam interference was measured using the fog chamber.

REFERENCES

[1] S. Lloyd, "Enhanced sensitivity of photodetection via quantum illumination," Science **321** 1463-1465, (2008).

[2] S. H. Tan, B. I. Erkmen, V.Giovannetti, S. Guha, S. Lloyd, L. Maccone, S. Pirandola, and J. H. Shapiro,"Quantum illumination with Gaussian states," Phys. Rev. Lett. **101** 253601, (2008).

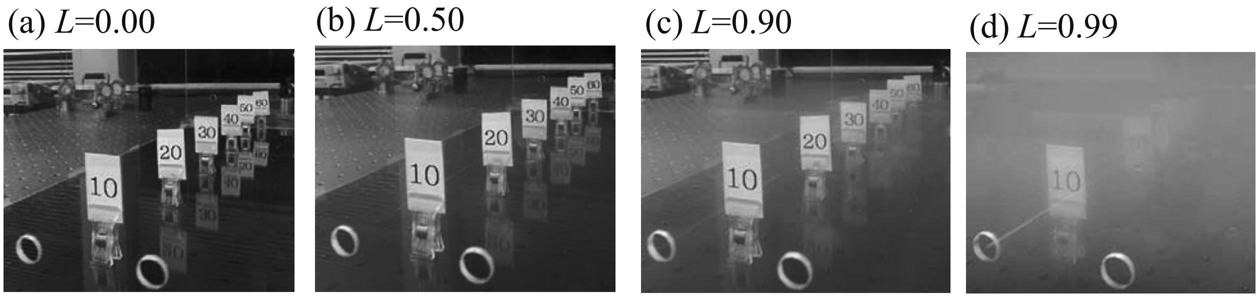

Fig. 3. Inner views of the fog chamber were observed by a digital camera from the side of laser beam entrance with optical losses (a) L=0.00, (b) L=0.50, (c) L=0.90, and (d) L=0.99, respectively. Significant Mie scattering of the laser light beam caused by the dense fog was observed at higer optical-loss conditions.

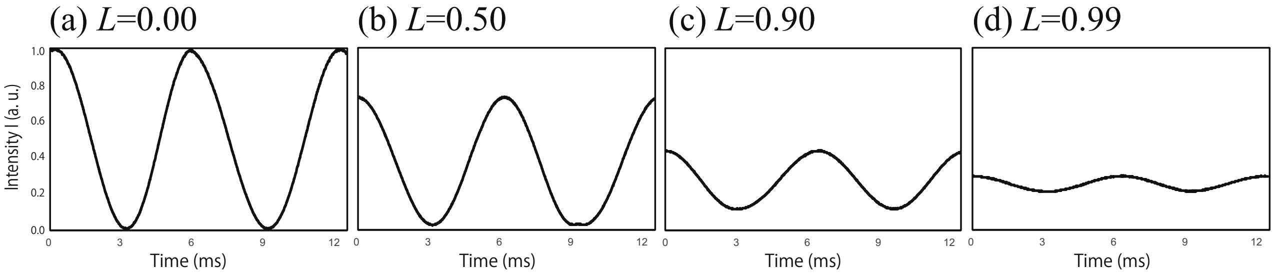

Fig. 4. Measurement results of interference signals using Mach-Zehnder interferometer. Only the signal beam is propagating through the fog chamber with optical loss of (a) L=0.00, (b) L=0.50, (c) L=0.90, and (d) L=0.99, respectively.

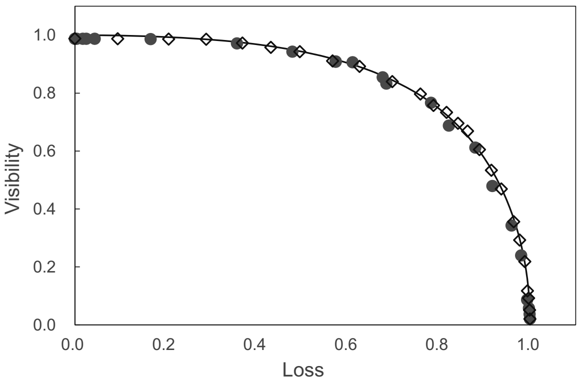

Fig. 5. Results of visibility measurements and calculation results. Solid circles are experimental results with the signal beam propagating through the fog chamber. Open diamonds are experimental results using a neutral density ND filter instead of the fog chamber. Solid curve is calculation results assuming only the energy loss L.

[3] J. H. Shapiro, and S. Lloyd, “Quantum illumination versus coherent-state target detection,” New J. of Phys. **11** 063045, (2009).

[4] G. Masada, “Verification of quantum entanglement of two-mode squeezed light source towards quantum radar and imaging ,” Proc. SPIE **10409** Quantum Communications and Quantum Imaging XV, 104090P, (2017).

[5] L. M. Duan, G. Giedke, J. I. Cirac, and P. Zoller, “Inseparability criterion for continuous variable systems,” Phys. Rev. Lett. **84** 2722, (2000).

[6] R. Simon, “Peres-Horodecki separability criterion for continuous variable systems,” Phys. Rev. Lett. **84** 2726, (2000).

[7] G. W. Petty. “A first course in Atmospheric radiation,” 2nd ed., Sundog publishng, 2006.

[8] A. Ishimaru, “Wave propagaiton and scattering in random media,” Reissued by IEEE press and Oxford University press, 1997.