Direct Measurement of Scattered Light Effect on the Sensitivity in TAMA300

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Abstract

Laser interferometer gravitational wave detectors need vacuum tubes through which the laser beams pass. The light scattered from the arm cavity mirrors will make multiple reflections from the inside wall of the polished tube back onto the mirrors causing phase noise on the interferometer output beam. The TAMA300 has two 300-m length arms enclosed by vacuum tubes. By vibrating one of the tubes of the TAMA300, we directly observed the effect of scattered light on the displacement sensitivity. It was found that a tube vibration amplitude of $5.6\,\mu$m at 776.5 Hz increased the mirror displacement noise to 1.2×10^{-17} m. This noise level is consistent with the calculated noise due to the scattered light effect.

1. Introduction

Noise due to scattered light from the surface of beam tubes is one of the noise sources in an interferometric gravitational wave detector. Although a large number of theoretical studies have been made on this noise (for example [1]), few experimental studies have been reported. We successfully confirmed the noise due to scattered light using a 100-m scale interferometer for the first time.

TAMA300, a Japanese gravitational wave detector, uses a 300-m Fabry-Perot type Michelson interferometer to detect tiny changes of the differential length between two orthogonal arms. The present instrument sensitivity is $h \sim 5\times10^{-21}\,/\sqrt{\mathrm{Hz}}$[2]. The beam from a Nd:YAG laser with a wavelength λ of $1.06\,\mu$m passes through two 300-m length beam tubes of 400-mm diameter. The inside surface of the stainless steel (SS) tubes are treated with an electro-chemical buffing (ECB) process in order to minimize outgassing[3]. The treated surfaces had roughness less than $0.4\,\mu$m. Therefore reflectivities of SS-ECB surface are almost 1 for large incident angle. Though the scattered light is low enough to obtain the present sensitivity, the noise caused by scattered light should be confirmed directly using TAMA300 in order to design the advanced detector. In this paper, we describe direct measurement of the scattered light effect on the sensitivity by vibrating the entire surface of the beam tube in TAMA300.

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2. Modeling of Scattered Light Noise

The main beam, which is resonated in the center of the cavity consisting of two mirrors, has power of P_0. The light power scattered from the near mirror and reflected only once from the beam tube surface toward the far mirror is proportional to the scattering properties of the mirror surface described by the bi-directional reflection distribution function BRDF(ϕ), to the magnitude of the incident light power, to the reflectivity of the beam tube surface, and to the magnitude of the solid angle into which the light is scattered. The power ratio of scattered light incident on the far mirror was calculated. In this expression, R is the reflectivity of the beam tube wall and ϕ is the scattering angle.

$$\frac{P_i}{P_0} = R \int_{\phi_{min}}^{\phi_{max}} \mathrm{BRDF}(\phi) 2\pi\phi \mathrm{d}\phi \tag{1}$$

The BRDF of the TAMA mirrors is not known. We used the BRDF of mirrors for LIGO[4].

$$\mathrm{BRDF}(\phi) = \frac{1000}{(1 + 5.302 \times 10^8 \phi^2)^{1.55}} \tag{2}$$

The scattered light incident on the far mirror re-scatters into the diffraction angle of the main beam and causes interference. The incidence angle at the far mirror, which is also the average scattering angle from the near mirror is

$$\phi_i = (\phi_{max} + \phi_{min})/2. \tag{3}$$

The diffraction angle of the main beam is equal to

$$\phi_{main} = \sqrt[4]{\frac{2\lambda}{\pi L}} \tag{4}$$

where L is the cavity length. Finally, the power ratio of scattered light into the interferometer beam is

$$\frac{P_{scat}}{P_0} = \frac{P_i}{P_0} \int_{\phi_i - \phi_{main}}^{\phi_i + \phi_{main}} \mathrm{BRDF}(\phi) 2\pi\phi \mathrm{d}\phi. \tag{5}$$

Since the path difference traveled by the scattered light is much greater than a wavelength of light, it is difficult to know the static phase difference $\Delta\Phi_{scat}$ of the scattered electric field vector E_{scat} in Fig. 1. However, the maximum phase fluctuation $\delta\Phi_{comb}$ of the combined noisy electric field vector E_{comb} occurs when $\Delta\Phi_{scat}$ is equal to zero or π. Then

$$\delta\Phi_{comb} = \frac{E_{scat}}{E_{main}} \delta\Phi_{scat}. \tag{6}$$

Squared E_{scat}/E_{main} corresponds to the power ratio P_{scat}/P_0 exactly. When the surface of the beam tube on which the light is scattered has radial displacement

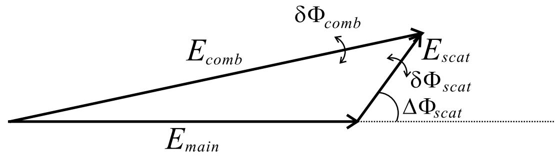

Fig. 1. Relation between the main beam E_{main} and the scattering light E_{scat}.

δz, optical path fluctuation of the scattered light with one reflection is equal to $\phi_i \delta z$. The phase fluctuation $\delta\Phi_{scat}$ is proportional to this optical path fluctuation. Therefore the mirror displacement noise caused by the scattered light is

$$\delta x = \sqrt{\frac{P_{scat}}{P_0}} \phi_i \delta z. \tag{7}$$

3. Experimental Setup

The beam tube was vibrated by a shaker vertically. To excite the maximum displacement of the scattered light with one reflection from the surface of the beam tube, the shaker was put between the frame for the gate valve to separate the tube at the mid point of the arm and the nearest tube support 2.7-m distance from the frame. Two different frequencies, 776.5 Hz and 788.5 Hz, were used to shake the tube. The tube surface has mechanical resonances at these frequencies. According to a modal analysis for the tube surface, the mode shape is an oval for the radial direction and has nodes fixed by the frame and the support for the axial direction. The higher mode with 788.5 Hz has two more nodes.

Two acceleration sensors were put on the tube surface. One is at a point as close as possible to the shaking point. The other is at a point near the optics which form the interferometer to investigate the noise caused by vibrating the optics directly. The amplitude of displacement at the shaking point was 5.6 μm for 776.5 Hz and 4.7 μm for 788.5 Hz respectively. Additionally we put a microphone in front of the door into the 300-m tunnel for the beam tube to investigate effects due to sound caused by shaking the tube.

4. Result and Discussion

We found excess signal at the tube excitation frequencies in the displacement spectrum of the interferometer (Fig. 2). One peak value of the signal due to the 776.5-Hz excitation was 1.2×10^{-17} m for the background level of 0.16×10^{-17} m. The other peak value due to the 788.5-Hz excitation was 0.25×10^{-17} m for the background level of 0.13×10^{-17} m. With comparison between outputs of two acceleration sensors, estimated direct effects due to vibration of the optics was less than 0.1×10^{-17} m for 776.5 Hz and 0.01×10^{-17} m for 788.5 Hz respec-

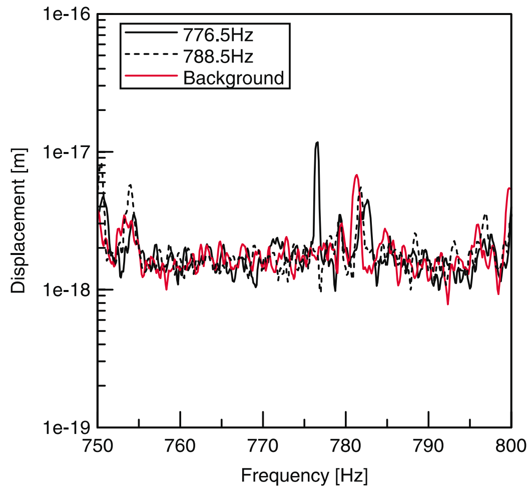

Fig. 2. Observed excess signal due to the beam tube excitation using two different frequencies, 776.5 Hz and 788.5 Hz.

tively. Therefore these effects were negligible. The door into the 300-m tunnel is effective in eliminating the sound due to shaking the tube. With the 776.5-Hz excitation we could not find any difference of the excess signal in the interferometer with the door open or closed. With the 788.5-Hz excitation there was a small difference of the excess signal. With comparison between outputs of the micro-phone in the 788.5-Hz excitation case, the estimated effects by sound due to shaking the tube was 0.2×10^{-17} m. Since the observed excess signal due to the 788.5-Hz excitation was comparable to the quadratic sum of the estimated sound effects and the background displacement noise level, we can not say that the excess signal is caused by the scattered light in this case.

The calculated value for the scattered light displacement noise is 6.3×10^{-17} m, assuming the static phase difference $\Delta\Phi_{scat}$ is optimal and the tube surface had common motion. A smaller value would have been calculated if the actual value of $\Delta\Phi_{scat}$ had been known. It therefore seems reasonable to suppose that the observed excess signal of 1.2×10^{-17} m with the 776.5-Hz excitation is caused by the scattered light in the beam tube. It is likely that the scattered light displacement noise caused by the 788.5-Hz excitation is partially cancelled by the higher mode motion of the surface on which the scattered light reflected.

5. References

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