Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

Density depependence of acoustic and acousto-optic characteristics of silica nanofaom

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PACS: 43.35.SX

ABSTRACT

In this study, we experimentally estimated the fundamental acoustic and acousto-optic characteristics of the nanofoam as functions of the density through acousto-optic measurements. A piezoelectric transducer is attached to a sample silicon nanofoam of $10\times10\times5$ mm^3 , and radiates a longitudinal sound wave into the sample. A He-Ne laser light at the wavelength of 632.8 nm was emitted through the sample in the direction perpendicular to the propagation of the ultrasound. Diffraction of the light wave by the ultrasonic waves was observed. The Raman-Nath diffraction occurs at a relatively low frequency since the sound speed is low, and the experiments was carried out at 510 kHz. The diffraction pattern agreed well with the Raman-Nath diffraction theory, and the sound speed was estimated from the diffraction angle. The sound speed varied 55~178 m/s for the sample density of 100~300 kg/m^3. The measured sound speed almost agreed with the sound speed calculated from the averaged density and bulk Young's modulus. Intensity ratio of the first order diffracted light to the fundamental light was 1 to 4 when the input ultrasonic intensity was 9 W/m^2 using a 200-kg/m^3 sample. This shows that the nanofoam has high acousto-optic efficiency than other conventional materials.

INTRODUCTION

Airborne ultrasound is widely used for sensing objects in robotics, production lines in factories, and other various kinds of applications[1]-[5]. Measurements of environments such as wind speed, snowfall, and traffic are also important applications of ultrasound in air. However, sophisticated signal processing can not be applied in airborne ultrasound technologies for higher performance because of the narrow bandwidth of conventional transducers. Silica nanofoam[6]-[14] is a porous material with a nanometer structure produced through a sol-gel process, and has been used as a heat insulator. It has hardly been applied to acoustic and acousto-optic devices. It is expected that the nanofoam may work as a good acoustic matching layer for airborne ultrasonic transducer for highly sensitive and wideband ultrasound transmission/detection since the nanofoam has an extremely low acoustic impedance. The nanofoam may also have a possibility as an acousto-optic device[15] because of its very low sound speed and optical transparency. The density and elastic properties of nanofoam in conjunction with the production process were studied in previous studies[7]-[11]. The density ranges between 4 and 12% of pure solid silica materials. However, acoustic/acousto-optic characteristics have not been investigated in detail yet.

In this study, we experimentally estimated the fundamental acoustic and acousto-optic characteristics of the nanofoam as functions of the density through acousto-optic measurements. A piezoelectric transducer is attached to a sample silicon nanofoam of $10\times10\times5$ mm^3 , and radiates a longitudinal sound wave into the sample. A He-Ne laser light at the wavelength of 632.8 nm was emitted through the sample in the direction perpendicular to the propagation of the ultrasound. Diffraction of the light wave by the ultrasonic waves was observed. The Raman-Nath diffraction occurs at a relatively low frequency since the sound speed is low, and the experiments was carried out at 510 kHz. The diffraction pattern agreed well with the Raman-Nath diffraction theory, and the sound speed was estimated from the diffraction angle. The sound speed varied 55~178 m/s for the sample density of 100~300 kg/m^3. The measured sound speed almost agreed with the sound speed calculated from the averaged density and bulk Young's modulus. Intensity ratio of the first order diffracted light to the fundamental light was 1 to 4 when the input ultrasonic intensity was 9 W/m^2 using a 200-kg/m^3 sample. This shows that the nanofoam has high acousto-optic efficiency than other conventional material.

Mesurement of diffracted light

We measured density dependence of sound speed from an angle of diffracted light. The angle of first-order diffracted light θ is calculated as follows.

$$\sin\theta = \frac{\lambda}{\Lambda} \quad (1)$$

where Λ is wavelength and λ is light wavelength. Silica nanofoam has very low sound speed (50~200 m/s). Therefore, we can observe diffracted light when frequency of ultrasound is less than 1 MHz. We measured light diffraction due to the acousto-optic effect. A 510 kHz ultrasonic transducer is attached to a silica nanofoam sample whose density varied 0.1 kg/m^3 to 0.3 kg/m^3. The light of He–Ne laser(λ = 632.8 nm) travels through the sample in the direction vertical to the ultrasound propagation. We adjusted the intensity of light using an ND filter. Diffracted light is measured by a photodetector scanned transversally to the direction of laser. The distance between the sample and the photo detector is 750 mm. Here, light intensity is detected by a lock-in amplifier with a frequency of a light chopper. Figrue 2 shows photo of the diffracted light pattern at 750 mm from silica nanofoam. Figure 3 shows diffraction light pattern (0.15 kg/m^3) at 750 mm from silica nanofoam. The sound speed was calculated using eq.(1) with the measured angle from figure 2.Then, the sound speed of silica nanofoam varied 57 m/s ~179 m/s. These values agreed with the sound speed measured from wavelength of standing waves. The wavelength of standing wave was measured by a light interferometer. These values also agreed with sound speed calculated by Young's modulus, Poisson ratio and density[16]. Figure 4 shows these sound speed of silica nanofoam and SiO_2. Lower density sample has lower sound speed. Figure 5 shows relationship between sound speed of silica nanofoam and frequency. Sound speed of silica nanofoam did not change in the range of 0.1 to 2 MHz.

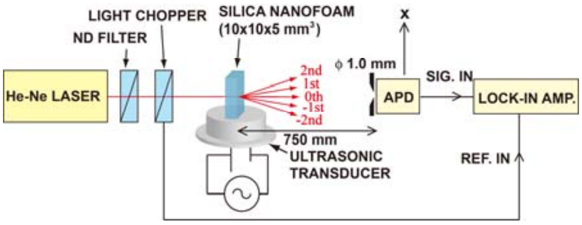

Figure 1. Experimental set upfor measureing diffraction light pattern

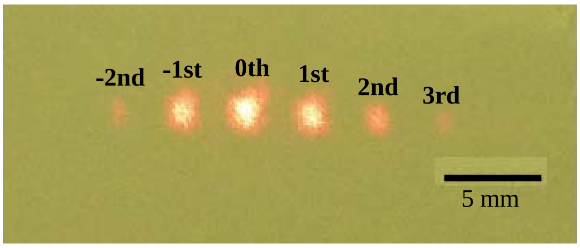

Figure 2. Photo of the diffraction light

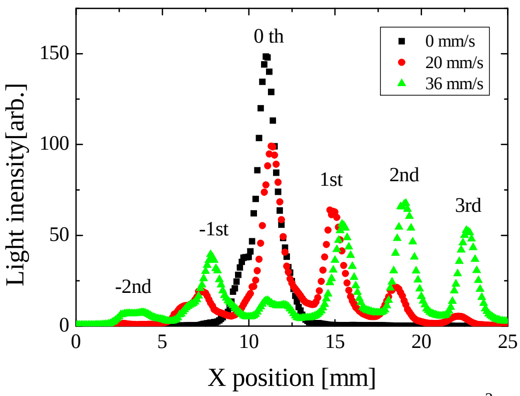

Figure 3. Diffraction light pattern (0.15 kg/m^3)

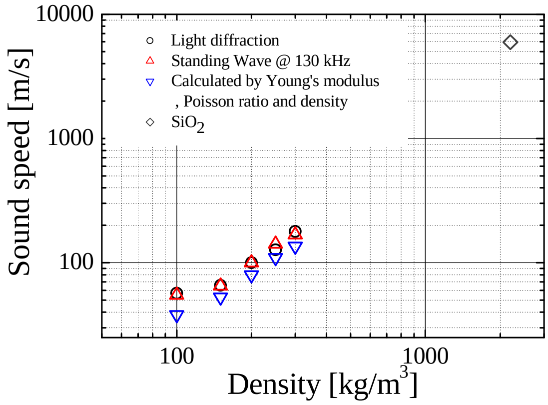

Figure 4. Sound speed vs. density

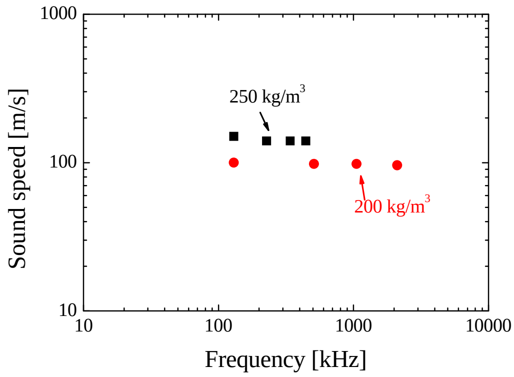

Figure 5. Sound speed vs. frequency

Efficeincy of diffracted light

Intensity of diffracted light I_m is written as follows:

$$I_m = J_m^{\ 2}(V), \quad V = \frac{2\pi \Delta n l}{\lambda} \tag{2}$$

where J_m is m-th order Bessel's function, Δn is change of refractive index, l is interaction length of sound wave and light wave, λ is light wavelength. When the intensity of the 0th-order light was half of the intensity without ultrasound, we measured vibration velocity of ultrasonic transducer. Figure 6 shows the relationship between the vibration velocity and the density. From these results, the lower density sample has the higher efficiency. Because lower density sample has larger deformation with the same sound pressure, a change of refractive index due to sound pressure is larger.

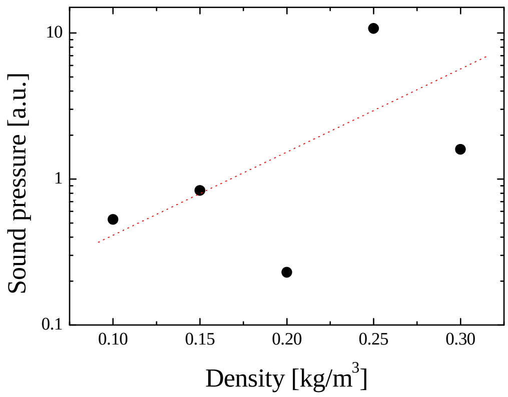

Figure 6. Sound pressure vs. density

Observation of the frequency shift of laser light in Raman-Nath diffraction

Frequency of laser light was modulated by ultrasound due to Raman-Nath diffraction. The 1st-order diffracted light and the -1st-order diffracted light went through a biconvex lens as shown figure 7. We observed interference of +1st-order and -1st-order diffracted lights at the focus of the lens using an avalanche photodiode. Figure 8 shows the measured waveforms of the applied ultrasonic voltage and the beat signal detected by the PD. The frequency of the beat is equal to the double of the ultrasonic frequenvy. These show that silica nanofoam has possibility of lower frequency acousto-optic device.

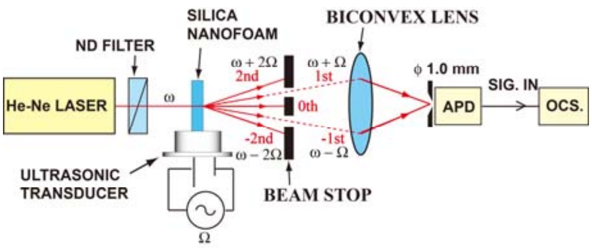

Figure 7. Sound pressure vs. density

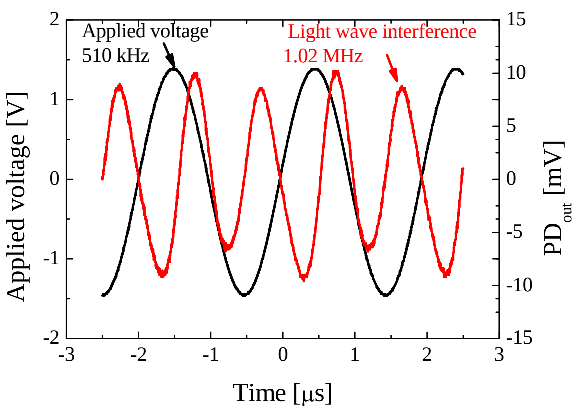

Figure 8. Waveforms of applied voltage and APD output

Conclusions

In this study, we measured density dependence of acoustic and acousto-optic characteristics of silica nanofoam. The Raman-Nath diffraction occurs at a relatively low frequency since the sound speed is low, and the experiments was carried out at 510 kHz. The diffraction pattern agreed well with the Raman-Nath diffraction theory, and the sound speed was estimated from the diffraction angle. The sound speed varied 57~179 m/s for the sample density of 100~300 kg/m^3. The measured sound speed almost agreed with the sound speed calculated from the averaged density and bulk Young's modulus. Intensity ratio of the first order diffracted light to the fundamental light was 1 to 4 when the input ultrasonic intensity was 9 W/m^2 using a 200-kg/m^3 sample. We observed interference of the +1st-order and the -1st-order diffracted lights. Frequency of the measured interference signal was twice of the frequency of the ultrasound. These show that the nanofoam has high acousto-optic efficiency than other conventional materials.

Acknowledgment

The authors would like to thank Mr. M. Hashimoto of Panasonic Corporation for providing the silica nanofoam sample.

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