ACOUSTIC AND ACOUSTO-OPTIC CHARACTERISTICS
OF SILICONE NANOFOAM

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ABSTRACT
Silicone nanofoam is porous material with nano-meter structure produced through sol-gel
process, and is used as heat insulator of electronic circuits. It is expected that the nanofoam
may work as a good acoustic matching layer of 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
because of its very small sound speed and optical transparency. In this study, we have
estimated the fundamental acoustic and optical characteristics of the nanofoam through
acousto-optic measurements. The sound speed and the acoustic attenuation were measured in
the frequency range of around 500 kHz using rectangular samples attached on a piezoelectric
transducer. Sound speed and acoustic attenuation constant were about 150~165 m/s and 2.78
dB/mm, respectively. Optical refractive index and its change rate due to sound pressure were
measured at the optical wavelength of 632.8 nm. Refractive index was about 1.075~1.080, and
the change rate in the refractive index of nanofoam material due to sound pressure was
approximately 2.58~2.96×10^-8 /Pa. Optical attenuation was 0.92 dB/mm for wavelength of
632.8 nm. Diffraction light due to interaction between light and ultrasound was observed.

INTRODUCTION
Airborne ultrasound is widely used for sensing objects in robotics, production lines in factories
and other various kinds of applications. 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 used in airborne ultrasonud technologies for higher performance
because of the narrow bandwidth of the conventional transducers. Silicone nanofoam[1] is
porous material with nano-meter structure produced through sol-gel process, and has been
used as heat insulator of electronic circuits. It is expected that the nanofoam may work as a
good acoustic matching layer of 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 because of
its very small sound speed and optical transparency. In this study, we estimate the fundamental
acoustic and optical characteristics of the nanofoam through acoustic-optic measurements such
as sound speed, acoustic attenuation, optical refractive index and optical attenuation, as well as
the change rate in the optical refractive index of nanofoam due to acousto-optic effect.

ACOUSTIC CHARACTERISTICS OF SILICONE NANOFOAM
Measurements of sound speed and acoustic attenuation
Figure 1 illustrates the set up for measuring the sound pressure inside a nanofoam sample. A
sample silicone nanofoam of 10-mm square and 5 mm in thickness is attached on an ultrasonic
transducer resonating at 510 kHz. We measured sound pressure radiated through sample by a
laser Doppler velocimeter (LDV) via acousto-optical effects. The light of the LDV is transmitted
through the sample in the direction perpendicular to the propagation of the ultrasound, and is
reflected back to the LDV head by using a mirror located outside the sample. The optical path
length is modulated by the ultrasound via the acousto-optic effect of the sample. Here, the
change in the optical path length $n\times l$ is measured as the change in the length $l$ using the LDV. 

Relationship between the actual change rate in optical refractive index of medium $\Delta n$ and the virtual change in the length $\Delta l$ is given by

$$\Delta n = \frac{n}{l} \Delta l = \frac{n}{2\pi l} v_{LDV} \quad \text{(Eq. 1)}$$

where $n$ is the optical refractive index of medium, $l$ is the length which interacts between the sound field and the light, $f$ is the frequency of the radiated sound, $v_{LDV}$ is the vibration velocity indicated by the LDV. The change rate in the refractive index for air (1atm and 15°C) is $\Delta n = 2.0 \times 10^{-9}/\text{Pa}$, and the sound pressure in air is measured as $[2]$

$$p[\text{Pa}] = 7.99 \times 10^4 \times \frac{v_{LDV}[\text{mm/s}]}{f[\text{kHz}] \times l[\text{mm}]} \quad \text{(Eq. 2)}$$

if the LDV light travels outside the sample. Sound pressure in the silicone nanofoam is estimated by the sound pressure in air and the transmission coefficient at the boundary between the sample and air. Transmission and reflection coefficients are expressed by the acoustic impedances of the silicone nanofoam $Z_1$ and air $Z_2$ as:

$$T = \frac{P_{air}}{P_{Si}} = \frac{2Z_2}{Z_1 + Z_2} = \frac{2 \times 428.6}{30000 + 428.6} = 0.028, \quad \text{(Eq. 3)}$$

$$R = \frac{Z_1 - Z_2}{Z_1 + Z_2} = \frac{30000 - 428.6}{30000 + 428.6} = 0.97. \quad \text{(Eq. 4)}$$

Here, we assume $Z_1 = 30000 \text{ kg/m}^2/\text{s}$ from the literature [1]. Figures 2 and 3 show the sound pressure and phase along the direction of propagation both in the sample and air by the method stated above. From the figure 2, the sound speed and the acoustic attenuation at 500 kHz are estimated to be 150~165 m/s and 2.79 dB/mm. From the figure 3, the sound speed and the acoustic attenuation at 510 kHz are estimated to be about 149~151 m/s and 3.25 dB/mm.

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Figure 1.- Experimental set up

Figure 2.- Sound pressure distribution in the silicone nanofoam at 500kHz: (a), amplitude; (b), phase
Acoustic attenuation at 40 kHz

We estimated the acoustic attenuation of silicone nanofoam also at 40 kHz being based on another method. The samples are inserted between a transmitter and a receiver as shown in figure 4. The number of samples is changed from 1 to 6. The received signal level is plotted against the total thickness of the samples in figure 5. Acoustic attenuation is estimated as 0.43 dB/mm.

Figure 4.-Experimental set up of measurement acoustic attenuation

Figure 5.-Sound attenuation due to thickness of silicone nanofoam

Figure 6.- Attenuation vs. frequency
OPTICAL CHARACTERISTICS OF SILICONE NANOFOAM

Optical refractive index

We estimated the optical refractive index of silicone nanofoam from the refraction angle when a laser ray travels through a corner of a square sample. By referring figure 6, Snell’s law is expressed in

\[
\begin{align*}
\sin \theta_{\text{air}} &= \sin \theta_{\text{sil}} \cdot n_{\text{air}}, \quad (\text{Eq. 5}) \\
\sin \theta_{\text{air}} &= \sin \theta_{\text{sil}} \cdot n_{\text{air}}. \quad (\text{Eq. 6})
\end{align*}
\]

According to the geometric nature,

\[
\theta_{\text{sil}} + \theta_{\text{sil}} = \frac{\pi}{2}, \quad (\text{Eq. 7})
\]
\[
\theta = \theta_{\text{air}} - \theta_{\text{air}}. \quad (\text{Eq. 8})
\]

Then, from Eq.5-8, we have

\[
\begin{align*}
\sin \theta &= \sqrt{\sin^2 \theta_{\text{air}} + \sin^2 \theta_{\text{sil}},} \\
\sin \theta &= \sqrt{\sin^2 \theta_{\text{air}} + \sin^2 \theta_{\text{sil}}}, \quad (\text{Eq. 9})
\end{align*}
\]

where \(n_{\text{air}}\) and \(n_{\text{sil}}\) are refractive index of air and silicone nanofoam, respectively. \(\theta, \theta_{\text{air}}, \theta_{\text{air}}, \theta_{\text{sil}},\) and \(\theta_{\text{sil}}\) indicate the angles shown in figure 7. We measured the refraction angle \(\theta\) and found \(n_{\text{sil}}=1.075-1.080\).

![Figure 7.-Experimental set up of measurement of refractive index](image)

We estimated refractive index of silicone nanofoam using another shape of sample referring figure 8. At the boundary between silicone nanofoam and air, we measured the incident and refractive angles. Incident angle was 62.5 degrees. Refractive angles were 72.4 degrees and 73.0 degrees at 650 nm and 532 nm, respectively. According to Snell’s low, we had

\[
\begin{align*}
n_{\text{sil}} \sin(62.5^\circ) &= n_{\text{air}} \sin(72.4^\circ), \quad (\text{Eq. 10}) \\
n_{\text{sil}} \sin(62.5^\circ) &= n_{\text{air}} \sin(73.0^\circ). \quad (\text{Eq. 11})
\end{align*}
\]

If the refractive index of air \(n_{\text{air}}\) is 1.000, the refractive indexes of silicone nanofoam \(n_{\text{sil}}\) are 1.074 and 1.078 at 650 nm and 532 nm, respectively.

![Figure 8.- Appearances of refractive light whose wavelengths are (a) 650 nm and (b) 532 nm](image)
Optical attenuation
We estimated the optical attenuation of silicone nanofoam by changing the number of samples. Light sources are a He-Ne laser (λ=632.8 nm) and a solid state laser (λ = 532 nm). We measured the transmitted light power by a photo detector. Optical attenuations are estimated 0.79~0.86 dB/mm and 1.43~1.52 dB/mm at 632.8 nm and 532 nm, respectively.

![Figure 9.-Experimental set up of measurement optical attenuation](image)

![Figure 10.-Optical attenuation vs. thickness of the silicone nanofoam at (a) 632.8nm and (b) 532 nm](image)

![Figure 11.-Optical attenuation vs. wavelength](image)

ACOUSTO-OPTIC EFFECT
Measurement using a laser Doppler velocimeter
Using the set up shown figure-1, the change rate of the optical refractive index for 1 Pa was estimated to be 2.58~2.96 ×10⁻⁸. Next, we have observed light diffraction due to acousto-optic effect. 510 kHz ultrasonic transducer is attached to a silicone nanofoam sample. Silicone nanofoam is pushed by a stainless rod. Light source is a He-Ne laser (λ=632.8 nm). Diffraacted light power is measured by a photo detector scanned transversally to the direction of laser when the voltage to the ultrasonic transducer is 0 Vp-p and 20 Vp-p. The distance between the sample and the photo detector is 600 mm. Here, the light intensity is detected by a lick-in amplifier with the chopper light source. From figure 13, it is observed that light is diffracted by ultrasound. In figure 15, only the diffracted components are recorded by selecting the ultrasonic
driven signal as the reference for the lock-in detector. According to Raman-Nath diffraction theory \[3\] \[4\], primary and secondary diffracted lights are observed at ±2.00 mm and ±3.99 mm from the original incidence (x = 7 mm).

**CONCLUSIONS**

In this study, we have estimated the fundamental acoustic and optical characteristics of the nanofoam through acousto-optic measurements. The sound speed and the acoustic attenuation were measured at the frequency of 40 kHz, 500 kHz and 510 kHz using rectangular samples attached on a piezoelectric transducer. Sound speed and acoustic attenuation constant were about 150~165 m/s and 4.68 dB/mm at 500 kHz, 149~151 m/s and 5.97 dB/mm at 510 kHz. Acoustic attenuation at 40 kHz ultrasound was about 0.43 dB/mm. Optical attenuation were 0.79~0.86 dB/mm and 1.43~1.52 dB/mm at the optical wavelength of 632.8 nm and 532 nm. Optical refractive index was about 1.075~1.080, 1.074 and 1.078 at the optical wavelength of 632.8 nm, 650 nm and 532 nm. The change rate in the refractive index of nanofoam material due to sound pressure was approximately 2.58~2.96 ×10\(^{-8}\) 1/Pa. This value is much higher than that of air. Diffraction of light wave by ultrasonic wave in a nanofoam sample was observed. This study showed that the nanofoam has a very low sound speed and a moderate attenuation at ultrasonic frequency. The optical transparency with a small refractive index is also one of the features of the material. The large acousto-optic effect may arouse new applications.

**References:**


