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Lamb waves generated by laser

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Abstract: A modulated continuous wave argon ion laser has been used to get lamb waves in silicon membrane. In this report, the basic principles of conversion from optics to thermal then acoustic waves are deduced. The experimental set-up, the analysis of the results and the possible way to obtain a given mode of lamb wave are described.

Key words: laser; lamb waves; sensors
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1 Introduction

Since 1980s, a modulated laser combined with a sensitive detection technique has been widely used to generate waves at a specific point on the surface of a sample, such as silicon, metal and paper, etc. Attractive features of such a source include the non-contact nature of the source with repeatability and the capability to generate a variety of acoustic modes.

A unique feature of the FPW (flexure plate wave) is that its phase velocity is lower than that of most liquids, and when FPW devices contacts such a liquid, a slow mode of propagation exists in which there is no radiation from the plate. Moreover, for an ideal liquid (no viscosity), energy of lamb waves can only be coupled into the liquid through the z component of displacement at the plate surface.

In our studies, we focused on the way to get stable zero mode lamb waves in silicon membrane which is sensitive enough to measure the change of a little mount of liquid on it.

2 Thermal-lamb wave principle

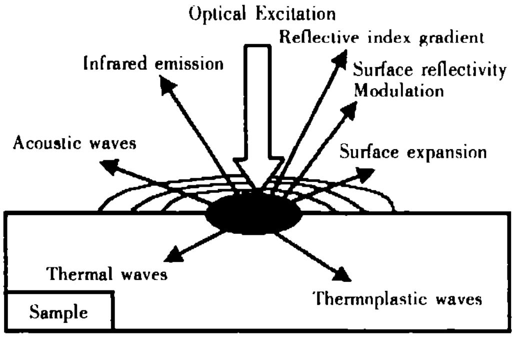

Fig.1 Results of a sample surface that exposed by light source

The results from the exposure of a sample surface to a localized periodically modulated light source is shown in figure 1. It can be seen that in addition to a change in temperature of the sample, the following secondary effects are also produced:

* modulated infrared emission from the surface.

* modulated thermal expansion resulting a distortion of the surface.

* generation and propagation of an acoustic wave.

* modulation of the optical properties of the surface such as the reflectivity.

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* modulated refractive index gradient in any gas or other transparent medium in contact with the heated surface.

Based on the conversion of absorbed optical energy, the thermal waves generated by laser were eventually converted into thermal energy. The excited electronic states in atoms or molecules will loose their excitations that result in a general heating of the materials.

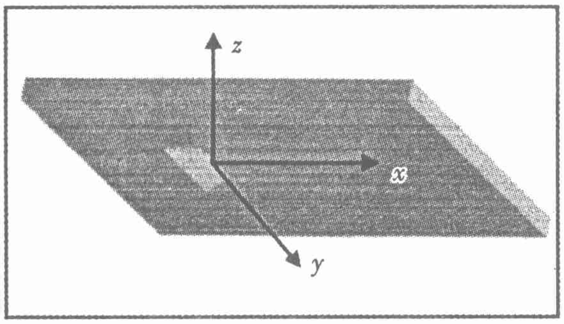

Fig.2 A silicon sample with membrane

The silicon sample with membrane is shown as Figure 2. The size of membrane is 3x8mm. The thickness is 15μm. Suppose:

* the silicon membrane is isotropic.

* the intensity distribution of the laser beam is Gaussian.

* the membrane got more freedom in x direction than in y direction.

So it can be assumed as a semi – infinite one – dimensional system. If the plane is harmonically heated by laser in form of $\frac{P}{\pi r^2}(1+\cos\omega t)$ in these conditions, subject to the boundary condition that the periodic thermal energy applied to the surface is dissipated by conduction into the solid, the heat flow rate equation of conduction will be:

$$-k\frac{\partial T}{\partial x} = \frac{I_0}{2}[1+\cos(\omega t)] =$$

$$Re[\frac{I_0}{2}(1+\exp(j\omega t))] \quad X < 0, t > 0 \quad (1)$$

If the heated surface is taken to occupy the y – z plane at x = 0, the temperature distribution within membrane can be obtained by solving one – dimensional heat diffusion equation (2) in x and t

$$\frac{\partial^2 T}{\partial x^2} - \frac{1}{\alpha}\frac{\partial T}{\partial t} = 0 \quad X < 0, t > 0 \qquad (2)$$

Separate variables of equation (2) as

$$T(x,t) = \varphi(x)\psi(t) \qquad (3)$$

And substitution (3) to (2), we get

$$\frac{\nabla^2\varphi(x)}{\varphi(x)} = \frac{\frac{d\psi(t)}{dt}}{\alpha\psi(t)} = \sigma^2 \qquad (4)$$

Where the left part depends on position and the right part depends on time , there should be a common constant σ^2 . From equation (5), we get

$$\nabla\varphi^2 - \sigma^2\varphi = 0 \quad \Rightarrow \varphi = A\exp(-\sigma x) + B\exp(\sigma x)$$

$$\frac{d\psi}{dt} - \alpha\sigma^2\psi = 0 \quad \Rightarrow \psi(t) = e^{-\alpha\sigma^2 t}$$

Where A and B are arbitrary constants. When x tends to infinity, T(x) must be finite, therefore the constant B is zero. The expression for A is evaluated by applying the flux continuity boundary condition at the sample surface, x = 0. Where $Re(\sigma) = \frac{1}{\mu} = \sqrt{\frac{\omega}{2\alpha}}$. The parameter μ is called the thermal diffusion length, which is a quantity analogous to the electromagnetic skin depth. The full solution is:

$$T(x,t) = \frac{I_0}{2k\sigma}\exp(-\sigma x + j\omega t) = \frac{I_0}{2\sqrt{\rho c k\omega}} \cdot$$

$$\exp(-x\sqrt{\frac{\omega}{2\alpha}})\exp j(\omega t - x\sqrt{\frac{\omega}{2\omega}} - \frac{\pi}{4}) \quad (5)$$

The thermal elastic equation is

$$(\lambda_0 + 2\mu_0)\frac{\partial^2 u_x}{\partial x^2} - \rho\frac{\partial^2 u_x}{\partial t^2} -$$

$$(3\lambda_0 + 2\mu_0)\alpha\frac{\partial T}{\partial x} = 0 \qquad (6)$$

Combined with equation (5), we obtain the wave equation as

$$u_x = \frac{(3\lambda_0 + 2\mu_0)\alpha I_0}{2k\sigma[\rho\omega^2 - (\lambda_0 + 2\mu_0)\sigma^2]}e^{-\alpha x} \qquad (7)$$

It shows the relationship among amplitude, sample characters and the energy of light source. If the waves can be written as harmonic oscillation,

$$A(x) = A\sin(2\pi\frac{x}{\lambda}) + B\cos(2\pi\frac{x}{\lambda})$$

For a given system, we have

$$\lambda f \equiv v_{0 = constant} \qquad (8)$$

When the thickness of membrane → 0, from VIKTOROV and ROYER we can get

$$v_0 = \frac{1}{2}k'd\sqrt{\frac{E}{3(1-\sigma_0^2)\rho}} \tag{9}$$

3 Experimental Set-up

3.1 The laser generation and detection system

The main components of a photothermal system including an excitation source, a modulator, a detector, a signal processing and displacement system are shown in Figure 3. The power of the excitation laser is < 1W, and its diameter and wavelength are 1.5mm and 532nm, respectively. Using this system, the changes of reflectivity and the distortion of the surface were detected.

The change in reflectance in sample surface by temperature is

$$\frac{\Delta R}{R_0} = \frac{1}{R_0}\frac{\mathrm{d}R}{\mathrm{d}T}\Delta T \tag{10}$$

Where $(1/R_0)\,\mathrm{d}R/\mathrm{d}T$ is the coefficient of thermal reflectance of the sample. For most solids this coefficient ranges from 10^{-4} to 10^{-6} per degree.

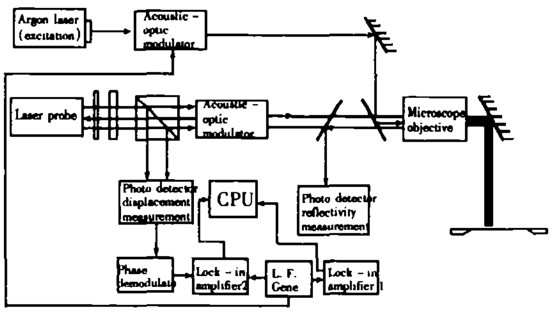

Fig.3 Optical bench for the membrane test

In the beam deflectance scheme, the modulated displacement of a probe beam reflected from the expanding and contracting heated region depends on the local slope of the displacement. The deflection signal at the position sensor is given by

$$S = X\left[2D\frac{\mathrm{d}u_x}{\mathrm{d}r} + 2u_x r_0 \sin\theta\right] + \textit{smaller terms} \tag{11}$$

Where D is the distance of the sample to the position sensor, u_x is surface displacement, θ is the angle of incidence of the probe beam and X is the position sensor's sensitivity. To gain a good approximation, the deflection signal is proportional to the displacement slope $\mathrm{d}u_x/\mathrm{d}r$.

3.2 Experimental set - up and results

Three kinds of experiments have been done with this membrane:

* laser heat membrane directly or through a big gap(more than 500μm)

* laser heat membrane through a silicon grating with equal gap of 200μm

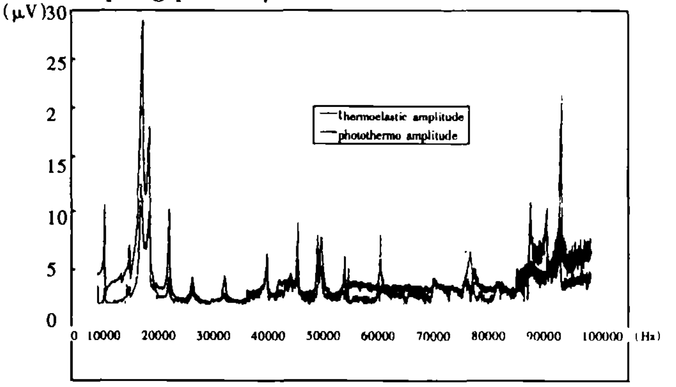

Fig.4 Laser heat membrane directly

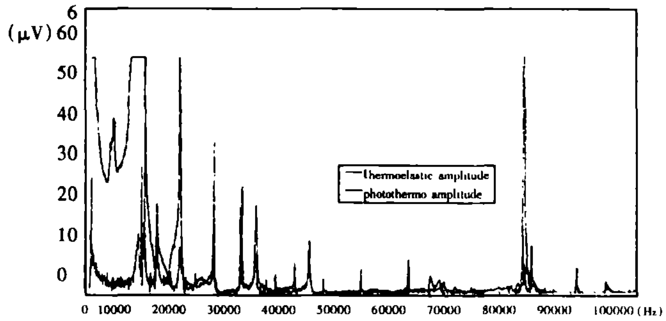

Fig.5(a) Laser heat membrane through a Si grating with equal gap of 200μm

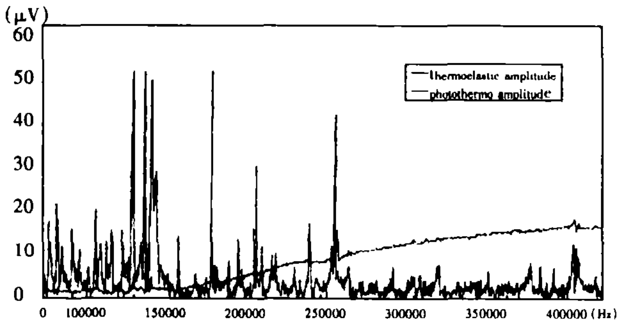

Fig.5(b) Laser heat membrane through a Si grating with equal gap of 200μm

Figure 4 and Figure 5 are photothermal

and thremalelastic signals, which we obtained from all of the experiments above respectively. We found that there were a lot of oscillations when the modulated frequency of laser is lower than 300kHz. From equation (9) we got the velocity of the waves V = 572m/s. So in figure 4 the wavelengths are from 44mm to 6.5mm. In Figure 5.1and 5.2 the wavelengths are from 57mm to 2mm. When the period of silicon grating changed, it seems that the thermalelastic and photothermal signals haven't changed very much. There aren't any signals when the frequency is over 300KHz. So even with the equal gap grating of 400μm period, we couldn't find the wave with wavelength of 400μm.

3.3 Analysis

It seems when the laser modulation frequency is lower than 300kHz, the heat absorbed by membrane during one period of grating is big enough to generate harmonic waves. So it's hard to get only one lamb wave in low frequency in this way.

From equation (5) we can see that the amplitude of temperature in membrane is proportional to the energy of laser and reversed proportional to $\sqrt{\omega}$. The heat diffusion length in this system with different modulation frequencies is shown in table 1 . When the exciting frequency is over 300kHz, the diffusion length is less than 10μm. Besides, when the frequency increases to more than 300kHz, ΔT becomes very small. From equation (7), (10), (11), we know that the reflectance and displacement on the local surface of heating are not big enough to measure.

Table 1 Diffusion length changes with modulation frequency

f	100Hz	1kHz	100KHz	300kHz	500kHz	1MHz
$\mu(\mu m)$	533	168.5	17.49	9.7	7.54	5.34

Perhaps it is possible to generate one given mode of lamb wave in high frequency with a grating whose period is less than 400μm if we increase the power of laser beam and decrease the thickness of membrane to several micrometers.

4 Discussions

a) The upper oscillation limit of frequency in membrane depends on the energy, the diameter, the modulation frequency and the characters of membrane itself. When the sample is given, the phase velocity is given as equation (9). The relationship among wavelength, velocity and the frequency of thermal - lamb wave is shown in equation (10). In order to avoid the damage of sample surface, the power of the laser couldn't be too high. So choosing wavelength and thickness of the membrane correctly is very important for generating a given mode of lamb wave. Besides, the uniformity and the diameter of the laser beam are the main factors to be sure that there are several periods of grating work in the same time.

b)The grating used to given wavelength should be assured that there is no high reflection on its surface.

c) In order to get high frequency waves, the diffusion length should be more than 10μm.

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Symbols and abbreviations

$T(\omega)$	Periodic temperature at modulation angular frequency ω
k	Thermal conductivity
P	Power of the laser beam
r	radius of the laser beam
ω	modulation angular frequency
α	Thermal diffusivity
I_0	Optical intensity
Re	Real part of
σ	Thermal wave number
ρ	Density
c	specific heat
μ	Thermal diffusion length

λ_0	Lame constant	d	Thickness of membrane
μ_0	Lame constant	σ_0	Poisson' ratio
u	Surface displacement	R_0	Interface thermal wave reflection coefficient
λ_0	Wavelength	X	Position sensor sensitivity
f	Frequency of waves	D	Distance of the sample to the position sensor
v_0	Velocity of phase	θ	Angle of incidence of the probe beam
E	Yang's module	$R(\lambda)$	Optical reflectivity at wavelength λ
		k'	Wave number

参考文献:

[1] Almond D P, Patel P M. Photothermal Science and Techniques[M]. CHAPMAN & HALL, 1966.

[2] Martin Von Allmen, Andreas Blatter. Laser-beam interactions with materials[M], Springer-Verlay Nerlin Heidelberg, 1987, 1995.

[3] Frank S. Crawford, Waves, Berkeley: Cours de physiques, volume 3[M], Education Development Center, Inc., Newton, Massachusetts, 1968.

[4] Pierce S G, Culshaw B, Shan Q. Laser generation of ultrasound lamb waves using low power optical sources[J]. IEE Pro. Sci. Meas. Technol. 1998, 145(5): 244 - 249.

[5] Junru Wu, Zhemin Zhu. The propagation of Lamb waves in a plate bordered with layers of a liquid[J]. J. Acoust. Soc. Am. 1992, 91(2): 861 - 867.

激光激发兰姆波

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摘 要:用激光激发超声兰姆波是近年提出的一种新的微传感器构成方法。本文从光—热—声波转换的基本原理出发，推导出激光在硅薄膜中激发兰姆波的条件和产生给定模式兰姆波的方法，给出了具体的实验设置、初步实验结果和数据分析。

关 键 词:激光；兰姆波；传感器

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