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Laser-based Apparatus for Measuring the Elastic Constants of Materials

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1. Introduction

The resonant ultrasonic spectroscopy (RUS) system is a useful device for measuring the elastic properties of materials [1-2]. The system is based on the principle that the mechanical resonant response of a sample depends on the elastic moduli, density, and shape. Thus, by measuring the density and shape, the elastic moduli could be obtained by solving the inverse problem of relating the frequency response to elastic constants. RUS has many advantages over other ultrasonic techniques in that there is no need for corrections due to ultrasonic diffraction, the transducer properties play a secondary role and all the elastic constants are obtained with a single measurement. This technique is widely used in the fields of materials science, geophysics and nondestructive evaluation.

Resonant mode excitation and detection using conventional piezoelectric transducers is well established [1]. In this approach, a test sample is placed with a minimal contact force between the transmitting and the receiving transducers. A frequency generator is used to sweep the frequency of the excitation transducer and the receiving transducer detects the mechanical response. While it is a simple and cost effective approach, there are three key drawbacks to this approach. First, due to transducer contact, the vibrations are not fully free which causes signal attenuation and systematic error such as frequency shifts and peak splitting. Second, contact transduction is inadequate for application to soft materials or operation in hostile environments. Third, the detection of RUS using a contact transducer does not enable high resolution spatial imaging. However, this issue is currently being addressed by using a laser interferometer for ultrasonic detection. In these cases the spatial resolution is determined by the optical spot size of the laser probe beam at the sample surface.

Recently, laser resonant ultrasonic spectroscopy (laser-RUS), a fully non-contact approach, has been studied as an improved tool for measuring the mechanical properties of materials [3-4]. Laser-RUS entails thermo-elastically exciting resonant modes by irradiating a sample with a pulse laser. A second continuous wave laser interferometer is used to measure the out-of-plane surface motion associated with the vibrating sample. There are two distinguishing features of laser-RUS: 1) All of the resonant modes are excited simultaneously (broadband excitation), 2) Mechanical coupling to the sample is minimized (i.e. the sample must be supported with small acoustically mismatched pins). The non-contact nature of this approach has great utility for the in-situ evaluation of mechanical properties in harsh environments (e.g. high temperature, high radiation) and for measuring the elastic properties of a soft material. Though the signal-to-noise ratio of this system is low, it has many advantages by virtue of having no mechanical coupling.

In this paper, a fully non-contact apparatus for measuring elastic constants based on the laser beams is fabricated. Here, a pulse laser beam is used to generate resonant laser ultrasound in a specimen and a confocal Fabry-Perot laser interferometer is used to measure the resonant surface vibrations of a specimen. The unstably varied gain of the confocal Fabry-Perot interferometer maintained a constant value within a limited gap by using a designed static stabilizer. This configured apparatus is adequate for measuring the elastic constants for a small sample. The measured signal and experimental result are described through experiments in this paper.

2. Fabricated Laser Resonant Ultrasonic Spectroscopy System and Experiments

A block diagram and a photograph of a fabricated laser resonant spectroscopy are shown in Fig. 1 and Fig. 2, respectively. This system consists of a pulse laser (Brilliant-B, λ=532nm, Quantel), a CFPI (Confocal Fabry-Perot Interferometer, CFT-500, Buleigh) with a CW laser (M142H, λ=532nm, Lightwave Electronics), a static stabilizer, and a digitizer.

Resonant laser ultrasound is generated whenever a laser beam is targeted onto the surface of a sample through a focusing lens. The laser ultrasound is generated by thermal expansion in the elastic regime. If a pulse beam is targeted onto the surface of a sample, then the CFPI using a measuring CW laser beam measures the surface displacement in the out-of-plane direction caused by the resonant ultrasound at an opposite corner of the sample. The linear polarized CW laser beam is focused onto the surface of an object after passing it through a half-wave plate (HWP), a polarized beam splitter (PBS), a quarter-wave plate (QWP), and a focusing lens (L). And then the backscattered light enters the CFPI cavity after passing it through the L, QWP, and PBS. The resonant ultrasound will be detected after the laser beam is demodulated by the CFPI. The transmitted optical signal is converted to an electrical signal by a detector (APD: C3090E, PerkingElmer Inc.). The oscilloscope synchronized by a pulse laser beam digitizes the resonant ultrasonic signal. Here, the static stabilizer maintains the CFPI at a constant gain level.

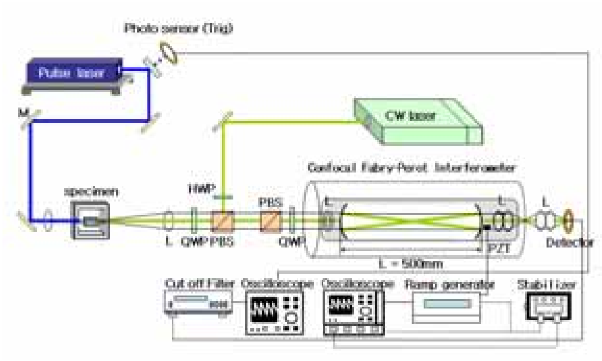

Fig. 1. Configuration of a laser-based resonant ultrasonic spectroscopy system

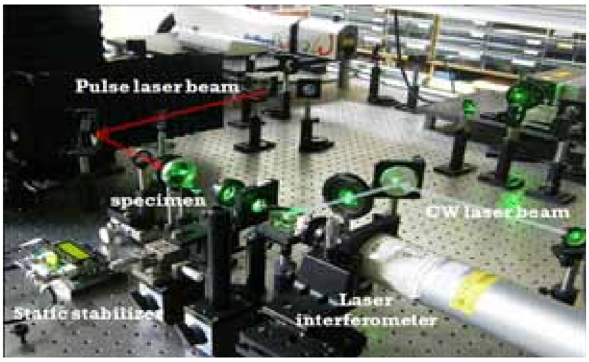

Fig. 2. Photograph of a configured laser-based resonant ultrasonic spectroscopy

A measured resonant ultrasonic frequency spectrum is shown in Fig. 3. As shown in Fig. 3, the laser-RUS excites all resonant modes at one time. So, the amplitude of each resonant peak is variable for each sample. The peak position of each resonant will contribute to the determination of the elastic constants of materials. The elastic constants of a specimen can be obtained from the measured resonant ultrasonic signals because the resonant response depends on its elastic constants, density, and its dimension. The elastic values can be extracted by solving the elastic wave equation of (1) under the condition (2).

$$\rho\omega^2 u_i + C_{ijkl} u_{k,lj} = 0 \qquad (1)$$

$$n_j C_{ijkl} u_{k,l} = 0 \qquad (2)$$

Here, ρ is the density of the sample, ω is the angular resonant frequency, u_i is the displacement vector's i_{th} component, C_{ij} represents the elastic tensor elements, n is the unit outer normal to the sample surface, and the comma indicates differentiation with respect to the coordinate just after the comma.

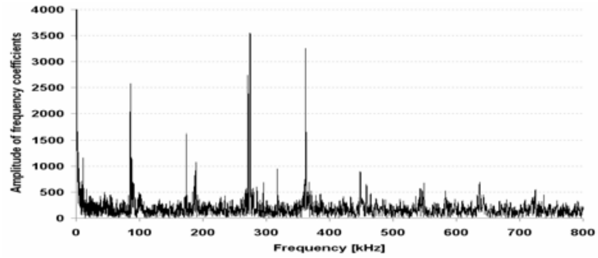

Fig. 3 A measured resonant ultrasonic frequency spectrum

The experimentally measured elastic moduli from the configured apparatus (a) are compared with results of voigt model (b) for a small Zr-2.5Nb specimen (W2.68xH2.24xL4.78) as shown in Table 1.

Table 1. Measured elastic moduli for a Zr-2.5Nb specimen

	C_{11}	C_{22}	C_{33}	C_{23}	C_{13}	C_{12}	C_{44}	C_{55}	C_{66}
(a)	1.42	1.49	1.63	0.83	0.72.	0.72	0.34	0.35	0.35
(b)	1.44	1.49	1.45	0.68	0.69	0.71	0.34	0.34	0.37

3. Conclusions

A basic laser-based apparatus for measuring elastic constants of materials was configured in this paper. This system provided elastic constants information of materials through experiments. The system could be adequate for the in-situ inspection of material properties.

For further research, two-wave mixing laser interferometer based on a photorefractive crystal is needed to acquire stable resonant ultrasonic signals and also, a scanning system is needed to improve the measurement resolution of the system.

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