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Proceedings of Symposium on Ultrasonic Electronics, Vol. 32 (2011) pp. 179-180
8-10 November, 2011

Development of a Picosecond-Ultrasonic System with a Stable Femtosecond-Pulse Fiber Laser

フェムト秒ファイバーレーザーを用いたピコ秒超音波システムの開発

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1. Introduction

Picosecond-ultrasonic (PU) method[1,2] has been used to evaluate physical characteristics of thin films. For example, by generating picosecond acoustic pulses in materials, elastic constants in the direction perpendicular to the film surface can be measured nondestructively[3]. Traditionally, this method has been carried out by the use of a Ti-sapphire (Ti/S) femtosecond-pulse laser. Ti/S pulse laser has a wide gain bandwidth, making it possible to generate ultra short light pulses. Also, its high-power output has made it applicable in many fields. In spite of these advantages, output stability of up to 3% has made it less attractive for measurements where expected signals are small compared to background noise. Thus, it is necessary to develop a picosecond-ultrasonic (PU) system using a more stable pulse laser.

In this paper, we develop a PU system using a highly stable femtosecond-pulse fiber laser. This Yb-doped fiber laser has output stability of up to 0.16%, more stable than the Ti/S pulse laser. Despite being more stable, the low output power has been the drawback to application to the PU method. We compare oscillation phenomena in thin films, typically observed by PU method, using PU systems incorporating Ti/S pulse laser and fiber laser, and discuss the useability of the fiber laser as optical source of PU system.

2. Optics

We construct the optics for picosecond-ultrasonic method using pulse fiber laser as shown in **Fig. 1**. The linearly polarized light pulse at the output has a wavelength of 1064 nm, pulse width of 150 fs, pulse repetition rate of 50 MHz. The light pulse is focused on a second-harmonic-generator crystal, where the wavelength of laser beam is changed to a visible 532 nm, and then propagates through a λ/2 wavelength plate, which rotates the polarization direction. The pump and probe light pulses are separated by a polarizing beam splitter. Their intensities are controlled by the λ/2 wavelength plate. The optical length of the pump light pulse is controlled by a mobile stage controller,

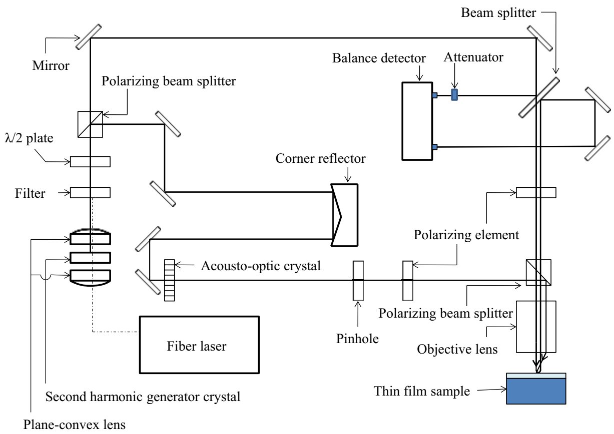

Fig. 1 Schematic of the optics. Solid and dashed lines represent laser beam with wavelength 532 nm and 1064 nm, respectively.

thus producing difference in optical lengths between pump and probe lights. The pump light irradiates the specimen surface to generate coherent acoustic pulses inside the specimen, and the time-delayed probe light is used to detect oscillation phenomena in the specimen.

3. Acoustic phonon resonance

Irradiation of an ultrathin film with the pump light pulse excites high frequency phonons, and certain phonon components remain. This causes the specimen to resonate at given frequencies. This is called acoustic phonon resonance, and the frequencies are given by $f = nv/2d$ for oscillations with free-free ends, and $f = (2n-1)v/2d$ for free-fixed ends, where n, v, and d represent mode order, longitudinal-wave velocity, and the thickness of the film, respectively. We measured acoustic phonon resonance of 20.3 nm-thick Pt film deposited on a quartz glass substrate by a sputtering method using the two different PU systems, incorporating fiber laser and Ti/S laser. As shown in **Fig. 2**, we observed acoustic phonon resonance from both systems. From the frequency equation above, we expect the fundamental-mode resonant frequency for this specimen to be 100.9 GHz. Conducting a fast Fourier transform (FFT) to the results in Fig. 2, we obtained frequencies of 99.5 GHz for fiber laser

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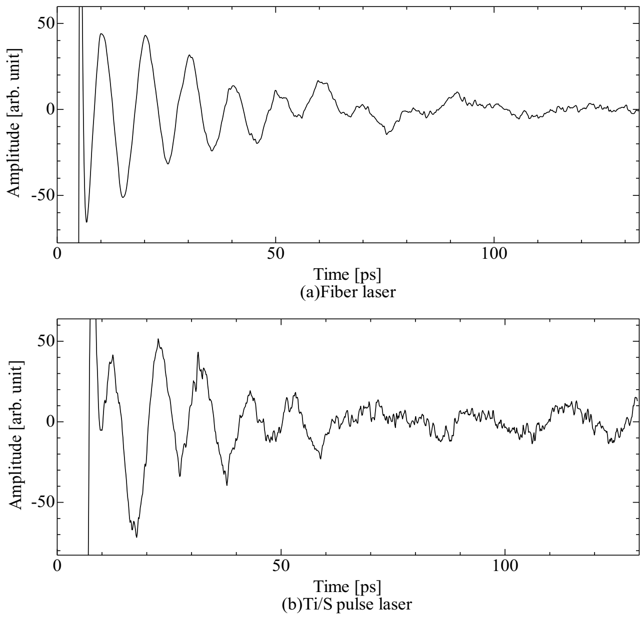

Fig. 2 Acoustic phonon resonance signals obtained from PU systems incorporating (a) fiber laser and (b) Ti/S laser.

system and 99.2 GHz for Ti/S laser system. These results agree well with the theoretical value, indicating that we succeeded in observing the acoustic phonon resonance of Pt thin film with newly developed optics with the stable fiber laser. Furthermore, larger signal-to-noise ratio is achieved with the fiber laser system (Fig. 2). This will be the consequence due to the stability of the source laser.

4. Brillouin oscillation

For transparent and translucent materials, the coherent acoustic pulse generated by the pump light pulse causes the reflectivity inside the material, which diffracts the probe light backward. Interference of the probe light pulses reflected at the surface and diffracted in the material causes periodic changes in reflectivity and phase of the reflected probe light as the acoustic pulse propagates inside the substrate. This is called Brillouin oscillation, and the oscillation frequency is approximately given by $f = 2nv/\lambda$, where $n, v,$ and λ represent the refractive index of the material, longitudinal-wave velocity, and wavelength of the probe light in vacuum, respectively. We measured Brillouin oscillation from an amorphous SiO_2 thin film, reactively deposited on (001) Si substrate. 10 nm of Al was deposited onto the thin film in order to excite acoustic pulses inside the film and substrate. **Fig. 3** shows the results of this measurement. The low and high frequency oscillations correspond to Brillouin oscillations from SiO_2 film and Si substrate, respectively. As the frequency of the Brillouin oscillation depends on the wavelength of the probe

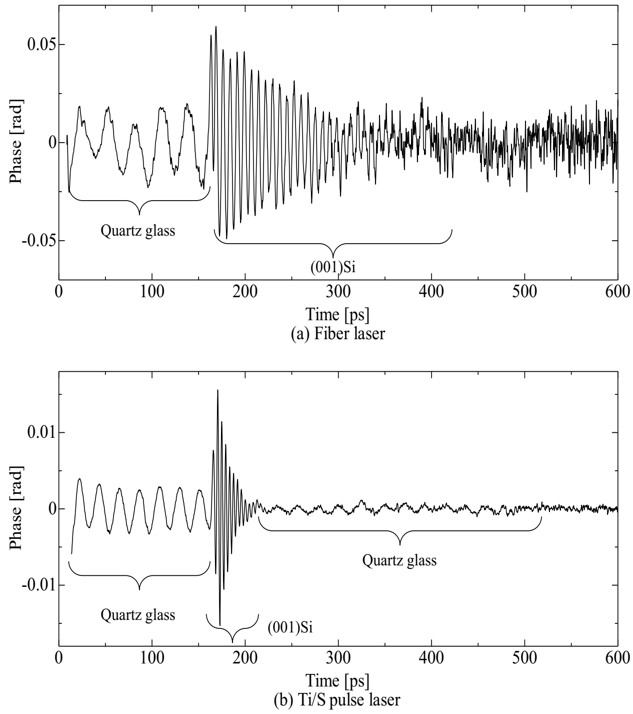

Fig. 3 Brillouin oscillations observed from SiO_2 thin film and Si substrate using PU systems incorporating (a) fiber laser and (b) Ti/S laser.

light, frequencies obtained from the two systems differ. For fiber laser system, with probe laser wavelength of 532 nm, the measured frequencies of Brillouin oscillations from SiO_2 and Si are 33.1 GHz and 131.4 GHz, respectively, which are close to the theoretical values of 33.2 GHz and 131.9 GHz. Also, it is obvious from **Fig. 3** that the Brillouin oscillation from Si substrate is more persistent when probed by 532-nm light. Attenuation of light inside Si highly depends on the wavelength, thus long-lasting oscillation phenomenon could be observed using fiber laser incorporated PU system.

5. Conclusion

We constructed a PU system using a stable fiber laser by dividing the light pulse into pump and probe light pulses by the polarization direction, not by the wavelength. The newly developed system showed higher signal-to-noise ratio and longer oscillation time in an optically lossy material than those with a traditional Ti/S laser system. Thus, it can be used for PU method and provide useful information for further research.

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